1. COVER PAGE

Office of Fossil Energy, U.S. Department of Energy

DE-FE0031783

Project: Conasauga Shale Research Consortium (CSRC)

PI: John B. Hickman, PhD
859-323-0541
John.hickman@uky.edu

Submitted by PI, John Hickman

October 31, 2021

DUNS Number: 939017877

Recipient Organization: University of Kentucky, Attn: Kim Carter
109 Kinkead Hall, Lexington, KY 40526

Project/Grant Period: October 1, 2019 through July 31, 2021

Reporting Period: October 1, 2019 through July 31, 2021

Final Technical Report

OSTI ID Number: 1836840

Signature of Submitting Official: ______________________________

John Hickman, PI

2. EXECUTIVE SUMMARY

The objective of the Conasauga Shale Research Consortium (CSRC) project was to establish a field laboratory and utilize a horizontal well of opportunity to conduct a scientific study designed to advance the understanding of the petrophysical and geomechanical properties of the emerging Rogersville Shale unconventional oil and gas play. Unfortunately, just as the research program was beginning, our industry partner lost a primary investor in the horizontal well which was intended to be the ‘well of opportunity’ for the project. In a negotiated restructuring of the project by DOE-NETL and the Awardee consortium, additional time for Budget Period 1 was granted in the hopes that the industry partner could acquire additional investments to allow for the drilling of the horizontal well. This search was ultimately unsuccessful, and the consortium was unable to pass the negotiated Go/No-go Decision Point #1, which resulted in the termination of the project on July 31, 2021.

Although no new well engineering or completion designs were tested due to the lack of a research well, considerable preliminary work was performed on the geology and geochemistry of the Conasauga Group rocks from existing data and geologic samples. The publishing of these new data and preliminary conclusions from the CSRC will aid future exploration companies make appropriate decisions regarding exploitation strategies for this potential resource. These new data include Cambrian-aged stratigraphic top depths from 225 wells in Kentucky, West Virginia, Ohio, Virginia, and Indiana, 56 XRD analyses of mineralogy, 20 programed pyrolysis (RockEVAL) analyses of potential source rocks, 20 petrographic bitumen reflectance (%BRo) analyses of thermal maturity, 240 analyses of Total Organic Carbon (TOC), 1,598 portable X-ray florescence (pXRF) elemental analyses, and critical analysis of recent uneconomic well completions within the Rogersville Shale of the Conasauga Group.

With the limitations of the abbreviated project schedule, formal conclusions and the production of a complete Development Strategy Plan are not possible. However, preliminary conclusions based upon these limited data suggest that only one organically rich zone capable of producing hydrocarbons exists within the Conasauga Group. This zone appears to be between 25 to 140 feet thick, contains between 1 and 4% TOC, and occurs near the middle of the Rogersville Shale interval, solely within the Rome Trough of eastern KY and southwestern WV. Although the interval is thermally mature (currently in the wet-to-dry gas window at an %Ro equivalent of ~1.67), the limited volume of source rock reduces the ultimate recovery potential of individual wells. Also, drilling and completion engineering challenges derived from the geology of the Rogersville Shale (high percentage of expandable clays, few natural fractures, and relatively under-pressured at depth) tend to result in expensive exploration wells. Although learned improvements in technique over time would surely improve the efficiency of drilling and completing a Rogersville Shale well, the apparent combination of limited recovery volumes from expensive wells does not appear to be an economic possibility at this time.

3. TASK REPORTS

The overall objective of the project was to establish a field laboratory and utilize a horizontal well of opportunity to conduct a scientific study designed to advance the understanding of the petrophysical and geomechanical properties of the Rogersville Shale. Understanding these properties will improve well placement and completion design, ultimately leading to commercial production and the acceleration of play development. The data generated and compiled in this project will then be integrated into a Rogersville Shale Development Strategy Plan that will enable oil and gas industry to accelerate the development of this emerging resource.

a. Task 1 - Project management

By John Hickman, PhD and David Harris

University of Kentucky – Kentucky Geological Survey

Lexington, Ky

This overall project was led by the PI's Hickman and Harris at the Kentucky Geological Survey (KGS) and managed by the University of Kentucky Research Foundation (UKRF) in Lexington, Ky. Work performed in West Virginia was managed by Patchen at the West Virginia University through a Subaward from UKRF to the West Virginia University Research Foundation (WVURF). The WVURF subsequently awarded a subcontract to the West Virginia Geologic and Economic Survey (WVGES) for additional well core analyses and geologic sampling of well cuttings and cores from Conasauga-penetrating wells in WVa.

The proposed BP-1 research was completed on-budget. Final budget details as of 10/31/21:

Dates	BP	DOE	Cost Share
10/19 - 7/21*	1	$ 646,816	$ 173,096
~~8/21 - 1/22~~	~~2~~	~~$1,430,446~~	~~$1,112,606~~
~~2/22 - 8/23~~	~~3~~	~~$3,062,820~~	~~$ 155,035~~
~~9/23 - 8/24~~	~~4~~	~~$ 908,912~~	~~$ 141,516~~
	Total:	**$ 646,816**	**$ 173,096**

* Note: Following completion of the original Budget Period #1 term, a 6-month No Cost Time Extension was requested by UK, and subsequently granted by DOE in order to give our industry partner (Hay Exploration, LLC) additional time to acquire well funding. This search for funding was ultimately unsuccessful, leading to the CSRC being unable to satisfy the contractual *Go/No-go Decision Point #1*. Therefore, the new end date for BP-1 and the overall Project is July 31, 2021.

The award for the Conasauga Shale Research Consortium began on October 1, 2019. Much of the first three months involved final contract negotiations between DOE and the Awardee (UK), and subcontract negotiations between the three research groups (UK, WVU, and WVGES). The project Kick-Off meeting was held between project researchers and DOE staff remotely (via WebEx) on December 18, 2019. All contracts were complete and accepted as of January 30, 2020. The management team at UK kept in regular contact with the project's industry partner, Hay Exploration, and monitored their search progress for the remaining investment funds throughout the project in order to drill the research well-lateral into the Rogersville Shale in Lawrence County, KY. Although some positive discussions with individual investors occurred, the recent oil price crash as well as the COVID-19 pandemic hampered that process, which was ultimately unsuccessful.

In March 2020, UK requested and received a 90-day No-Cost Time Extension to the CSRC project from DOE. In April 2020, UK extended the CSRC Subaward to WVU through August 30, 2020 to align it with the new, extended time frame for Budget Period 1. Although at-work locations and protocol changed dramatically due to the COVID-19 pandemic situation, the proposed research at UK, WVU, and WVGES continued on-schedule and on-budget.

In July 2020, Hay Exploration investigated the possibility of using an alternate Rogersville Shale well (Bruin Exploration #1 Walbridge in eastern Lawrence County, Ky) for the CSRC project at a reduced drilling cost to Hay (a pre-existing lateral exists in that well). Unfortunately, the surface owner at that location decided not to allow further development, so that plan was abandoned.

In a negotiated restructuring of the project by DOE-NETL and the Awardee consortium, additional time for Budget Period 1 was granted in the hopes that the industry partner could acquire additional investments to allow for the drilling of the horizontal well. This search was ultimately unsuccessful, and the consortium was unable to pass the negotiated Go/No-go Decision Point #1, which resulted in the termination of the project on July 31, 2021.

b. Task 3 - Data inventory and sample management

By John Hickman, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

Data Inventory

Task 3 was designed to produce accurate inventories of the publicly available data and geologic samples from the subsurface Conasauga Group of eastern Kentucky and southern West Virginia. The data and samples involved in this task are of three different categories: CSRC-funded, donated, and legacy. The CSRC-funded data are any data that came from analyses paid for by CSRC funds. (Unfortunately, because of the lack of the research lateral well in the shortened project period, no new geologic samples were acquired with CSRC funds.) The donated data and samples were acquired from the four operators which had recently drilled Rogersville Shale UOG wells (Cabot, Chesapeake, Cimarex, and EQT) in a data-sharing agreement with the state Geologic Surveys. The legacy data and samples are derived from the KGS and WVGES databases and sample facilities that have been collected over the past 60^{+} years.

The research teams from the Kentucky Geological Survey (KGS) and West Virginia Geologic and Economic Survey (WVGES) reviewed their respective oil and gas databases to produce lists of existing in-house (legacy) data. KGS loaded both the legacy and donated XRD, TOC, and %Ro tabular data points into Petra petrophysical software, and then converted them into pseudo “log curves” so that existing data-density by depth and formation could be visualized in a cross-sectional format of the relevant wells.

Data inventories for the two state surveys prior to the CSRC project are displayed in Table 1.

Table 1. *Data inventory totals, prior to CSRC research.*

Analyses	Kentucky	West Virginia	Totals
Total Organic Carbon (TOC), Wt%	461	437	898
X-Ray Diffraction minerology (XRD)	10	167	177
Pyrolysis (RockEVAL and equiv.)	303	206	509
Vitrinite Reflectance (%Ro)	5	4	9

Sample Management

In December 2019, KGS received a shipment from Cimarex Energy (part of a data sharing agreement with the CSRC) that included the well cuttings and rotary side-wall cores from two recent Rogersville Shale wells in Lawrence County, KY. Over 17 Gb of data related to these Cimarex (Bruin Exploration) wells has been successfully transferred to UK.

In February 2020, received the well data donation from Chesapeake Energy – Appalachia from their #15-S-84 Northup well in Lawrence County, KY (part of a data sharing agreement with the CSRC). This dataset included well logs, laboratory test results, core photos, thin-section photomicrographs, daily driller’s reports, wellbore schematics, and results from shut-in pressure tests. These data include a total of over 39 Gb of files.

In April 2020, KGS received a shipment of donated EQT well samples from the Horizontal Technology #572360 Caudill well in Johnson County, KY (part of a data sharing agreement with the CSRC). This included well cuttings, slabbed whole core, and rotary side-wall cores from the recent Rogersville Shale well that were previously at Stratum Reservoir labs (originally Weatherford Labs) in Houston. Overall, over 370 Mb of digital data related to the Caudill well was successfully transferred to UK-KGS.

Samples and data analyses within the WVGES database sourced from Conasauga units were extracted. The metadata for those eight wells are listed in the inventory of data table. Data includes the API, well names, location information, depth to the tops of Conasauga Group units, and the types of analyses preformed on samples from each well including the number of samples, depths used or depth range. The types of analyses include mercury injection, core lab GRI, pyrograms creation, kerogen and total organic carbon (TOC) measurements, scanning electron microscope (SEM) images, thin section analyses, core photos, Medical and/or Industrial X-ray computerized tomography scans, geophysical core logging, medium pressure liquid chromatography (MPLC) analysis of hydrocarbons, extractable organic matter (EOM), vitrinite reflectance, etc. In April 2020, WVGES provided these data to KGS.

KGS compiled Kentucky's tabular well data in a similar fashion, then loaded them into the project Petra database along with the West Virginia data detailed above. This permitted a visualization of the vertical spacing or density of the existing data within the Conasauga Group strata by way of stratigraphic well-based cross sections. A total of six cross sections were created in order to incorporate all of the previous wells that had penetrated the middle Conasauga (Rogersville Shale) or deeper horizons. Through these visualizations, KGS began picking intervals for new in-fill sampling for organic richness (TOC), clay minerology (X-ray diffraction, XRD), and thermal maturity (pyrolysis and %Ro) analyses.

In September 2020, KGS received the shipment of 724 feet of whole core donated by Chesapeake Energy – Appalachia from the #15-S-84 Northup well in Lawrence County, KY.

A trip to EQT's offices in Pittsburgh by KGS staff to collect the remaining donated geologic material was postponed in May 2020 because of UK's COVID-19 travel policy. The CSRC was able to overcome this challenge by negotiating a discounted-price freight shipment of these samples from the holding facility in Pittsburgh to KGS's core and sample facility in Lexington, KY in October 2020.

Throughout the project, WVGES staff continued communicating with Cabot Oil and Gas to acquire the samples and data from the Cabot #50 Amherst Industries well in Putnam Co., WV. After several delays, in February 2021 WVGES was able to coordinate with Cabot Oil and Gas to acquire the samples and data from the Cabot #50 Amherst Industries well in Putnam Co., WV. Cabot Oil & Gas supplied WVGES both digital well data (Figure 2) and physical well samples. The digital data from Cabot was shared with KGS in its entirety.

Figure 1. *Pallets worth of geologic samples (well drill cuttings and rotary sidewall cores) from the Cimarex donation to CSRC.*

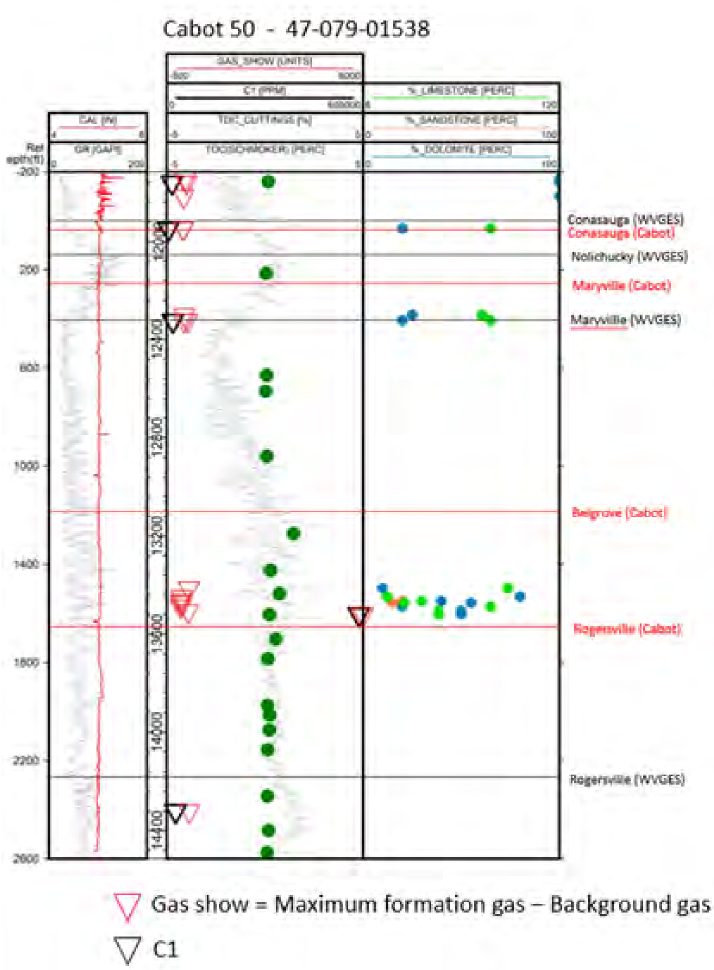


Figure 2. *Example of Cabot #50 Amherst Industries dataset including well logs, gas shows, calculated lithology, and measured TOC of samples.*

c. Task 4.1 - Review of Rogersville Well Completions

By Richard Bowersox, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

<u>Project Summary</u>

This evaluation of the Rogersville Shale commenced in 2019. At that time six wells had been drilled into, and four wells completed in the Rogersville by four operators (Figure 1–2): Cimarex Energy Company, operating as Bruin Exploration, LLC (two wells); EQT Corporation, operating as Horizontal Technology Energy, LLC; Cabot Oil & Gas Corporation; and Chesapeake Appalachia, LLC (two wells). Two wells drilled by these operators have been excluded from this evaluation. The Chesapeake LAW 1 Janet Stephens et al. ("1 Stephens" well herein and in Subtask 7.10), found a thick section of sandstone and siltstone where Rogersville shale should have been present in the stratigraphic section, and the Cabot 50 Amherst well did not reach the Rogersville at its total drilled depth (TD) of 14,250 ft. Of the remaining four wells, none were completed to commercial production, for reasons discussed below, and were plugged and abandoned as required by Kentucky oil and gas regulations. The play abandoned by all operators by 2020. Preliminary results of this evaluation were presented at the 50th Annual Meeting of the Eastern Section, American Association of Petroleum Geologists, Pittsburgh, Pennsylvania (Bowersox et al., 2021).

<u>Methodology</u>

The four operators in the Rogersville play provided robust datasets to the Kentucky Geological Survey for this evaluation including geophysical logs, core and drill cuttings sample analyses, operational data and well test reports, and well completion reports. Whole-diameter slabbed cores and drill cuttings from the wells were donated by the operators to the Kentucky Geological Survey (KGS) and deposited in KGS's Earth Analysis Research Library (EARL), Lexington, Kentucky. These datasets are the basis for the evaluation the Rogersville wells' completions and interpreting production performance. All four operators preferred drilling their wells using oil-based drilling muds which appears to have contaminated core and cuttings analyses in some instances and thus affecting data quality (Figure 3). Results of this evaluation are discussed individually for each well.

X-ray diffraction (XRD) mineralogy of drill cuttings and rotary sidewall cores (SWC) showed the section from 200 ft above to 200 ft below the potential completion interval in the Rogersville to have a clay content that was largely composed more than 18% expandable illite/smectite clays (Figure 4). This suggests that the completion would be sensitive to injection of any fresh water during hydraulic fracturing causing the clays to swell and plug porosity and fractures in the Rogersville. Fresh water sensitivity tests performed on cuttings from the Bruin 1H Walbridge horizontal wellbore showed the Rogersville to be highly sensitive to fresh water (Figure 5):

> The results show the cuttings samples to be moderately to highly sensitive to DI [deionized] water with CST [capillary suction time, i.e. water imbibition time] ratio values from 3.2 to 7.2. The remaining fluid all gave relatively

low sensitivity response with values just greater than 2. There was little difference in 0.5 and 1.0 gpt of the clay stabilizer, both giving values close to 7% KCl regardless of the fresh water source they were mixed in.

The results are not an unusual response for this clay stabilizer which coats the particles. The one issue to be concerned with is the fact that the CST test uses a higher fluid to rock ratio than what would be the case in the reservoir where the fluid is just filling the pores. Therefore, the CST does not account for depletion of the clay stabilizer from solution as the fluid leaks off deeper into the frac face. The CST is more an indication of what the fluid sensitivity would be like at or near the frac face where there is an excess fluid (and stabilizer) exposure. Core Lab report, *CST Fluid Sensitivity Results for Cuttings Samples from Walbridge 1H, Project SL12153*, dated December 22, 2016.

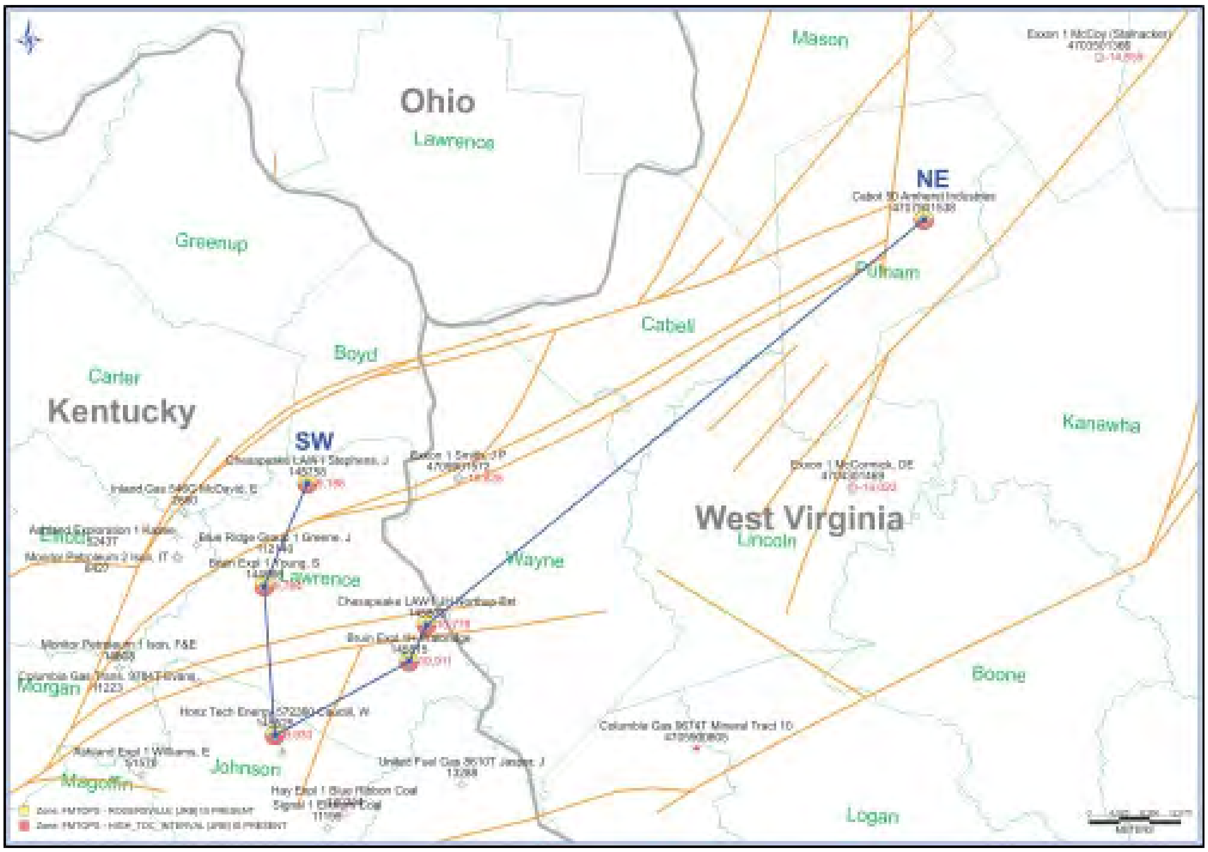


Figure 1. *Location of the Rogersville Shale evaluation region, northeastern Kentucky and southwestern West Virginia. Tan lines represent generalized basement fault locations.*

Results of this test suggest that the addition of clay stabilizers to fresh water during hydraulic fracturing would not mitigate clay swelling beyond the rock volume immediately surrounding the wellbore. By itself, swelling clays plugging porosity after hydraulic fracturing would be enough to condemn the Rogersville play.

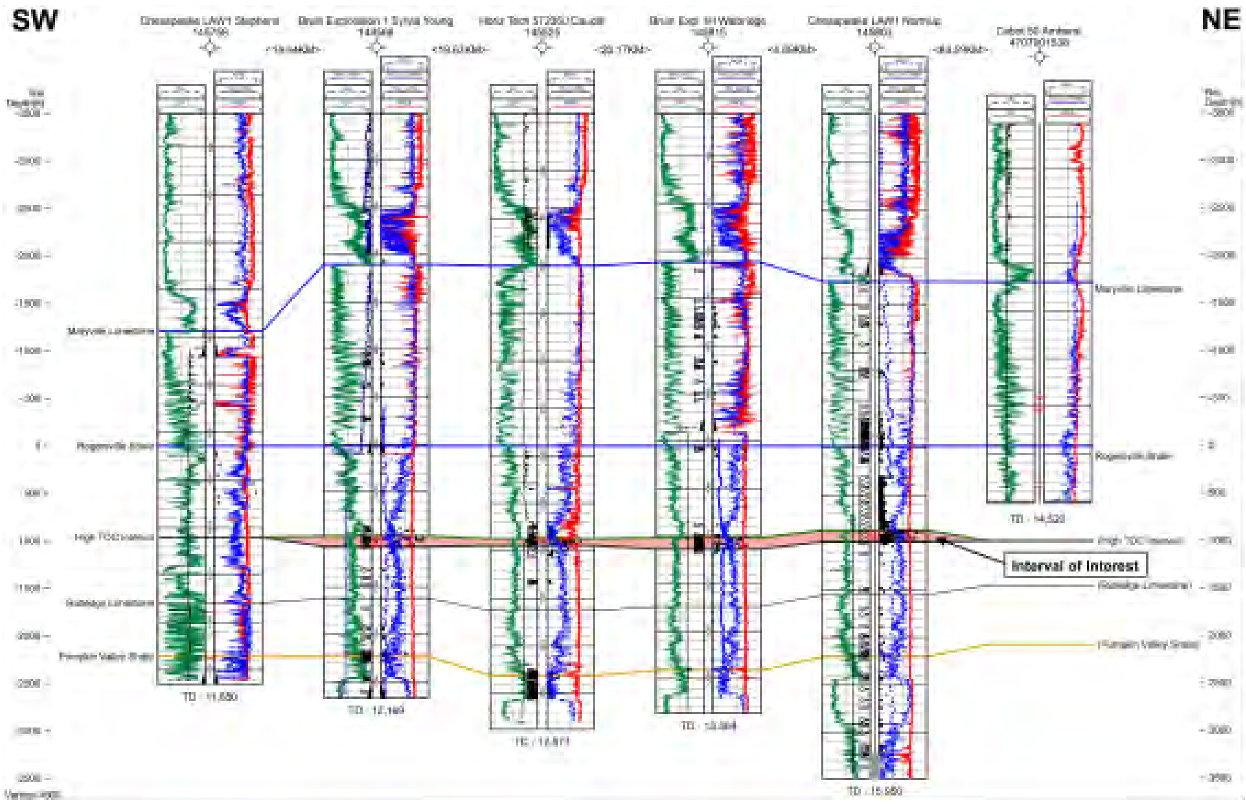


Figure 2. SW–NE stratigraphic cross section through the Rogersville Shale exploratory wells, northeast Kentucky and southwest West Virginia. Rogersville "high TOC" interval of interest is shown with the red fill. Vertical scale x500.

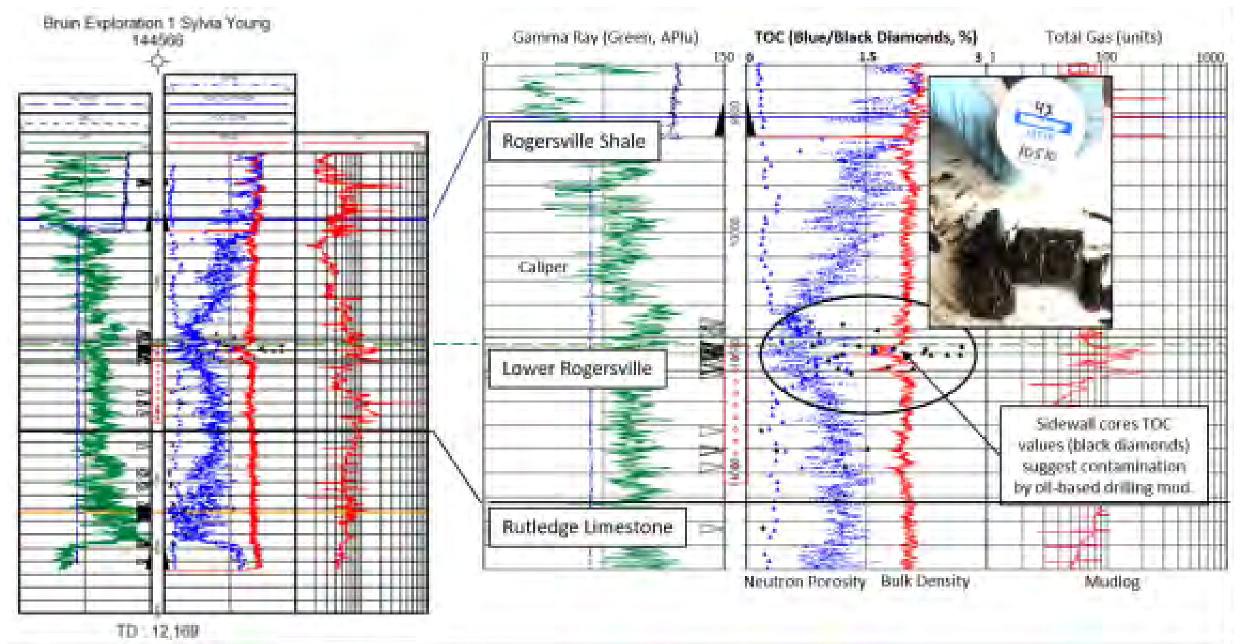


Figure 3. *Example of oil-based drilling muds affecting data quality in this evaluation. TOC values measured in rotary sidewall cores (black diamonds) noticeably spike compared to those measured in drill cuttings (blue diamonds) in the high-TOC interval.*

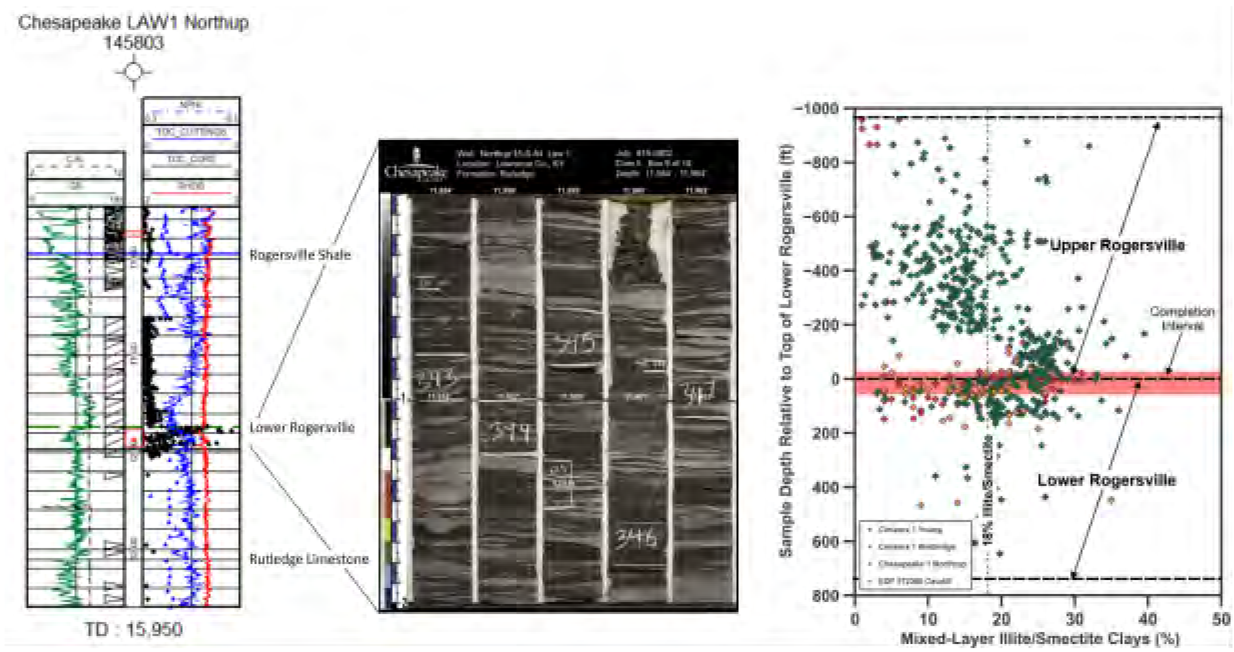


Figure 4. *Expandable clays in the Rogersville. The interval including the high-TOC interval (Figure 3) is also an interval with high-expandable clay content. Use of available fresh water to hydraulically fracture this interval could overcome any benefit of clay stabilizers in the fracture-treatment water.*

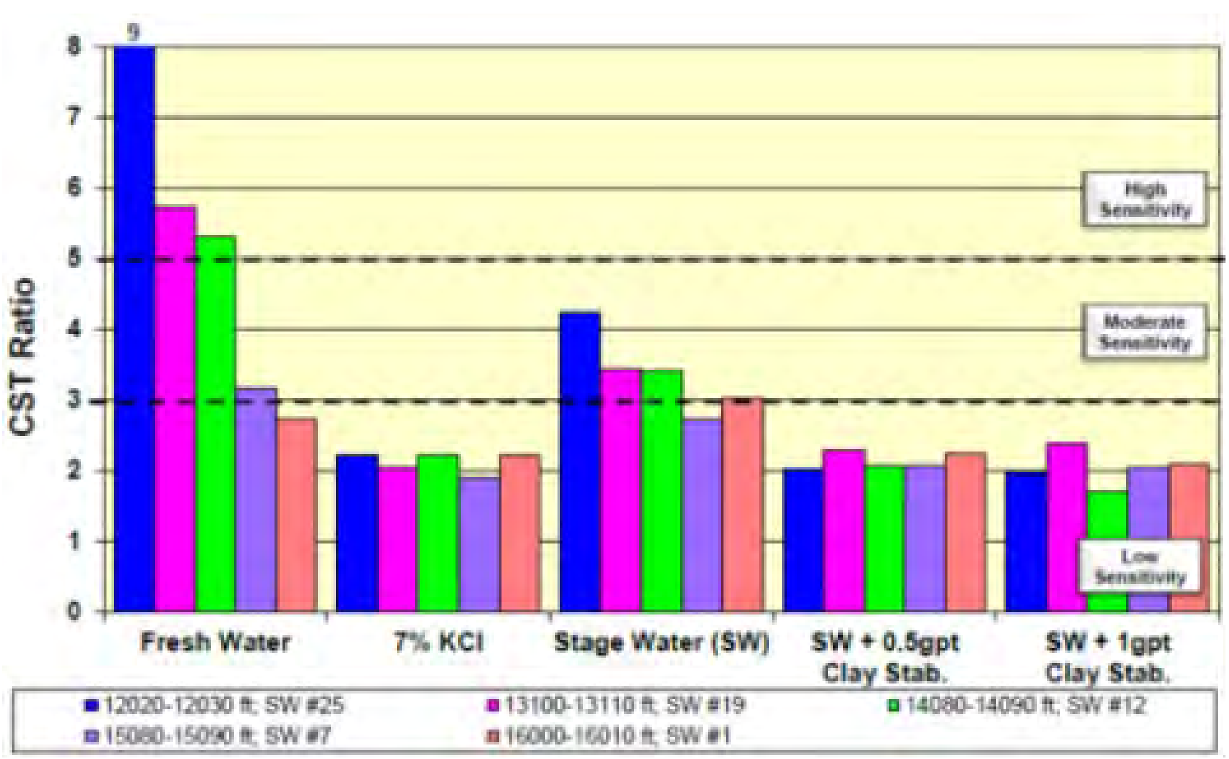


Figure 5. *Fresh water sensitivity tests of well cuttings from the Bruin 1H Walbridge well showing the effect of hydraulic fracturing staged water (SW) with and without clay stabilizers. This shows that the Rogersville is highly sensitive to fresh water.*

<u>Bruin Exploration 1 Walbridge</u>

The Bruin 1 Walbridge well, Lawrence County, Kentucky, was drilled to a total vertical depth of 13,362 ft KB (Figure 2) then horizontally redrilled as the Walbridge 1H well 5016 ft from 11,092–16,108 ft measured depth (MD) TD, 14,495 ft true vertical depth (TVD), and cased with 5½-inch casing cemented to TD. A mud log was made from 100 ft to TD and an extensive suite of resistivity, nuclear, and acoustic logs were recorded in two intermediate log runs and at TD. Laboratory tests of rotary sidewall cores or drill cuttings from the Rogersville are discussed elsewhere in this report. A borehole breakout log was recorded in the Bruin 1 Walbridge well in an intermediate logging run at 2775–10,390 ft to determine the orientation of the Rogersville fracture system. Orientation of the fracture system at 10,225 ft was N51.38°E, comparable to the regional N53°E fracture trend identified in the Knox Group (Bowersox et al., 2021). The horizontal wellbore was drilled S33°E, structurally down dip and approximately normal to the fracture system, likely to intersect the natural fracture system.

Prior to perforation and hydraulic fracturing, Haliburton performed a Diagnostic Fracture Injection Test (DFIT), in the Bruin 1 Walbridge near the toe of the horizontal wellbore casing at 16,100 ft MD (11,496 ft TVD) to characterize in situ reservoir properties in the Rogersville (Cimarex Walbridge Holdings LLC 1H, Lawrence County, KY, API #16-127-03200, DFIT Analysis Report, by Halliburton, dated 5 January 2017). The wellbore was filled with 7% KCl water (specific gravity 1.0435 at 20°C) prior to the test and 18.87 barrels mixed 50/50 7% KCl water and methanol pumped into the Rogersville for the test at a rate of 2.97 barrels per minute (BPM) for 7.6 minutes. The Rogersville fractured at 11,694.6 psi, a fracture gradient of 1.01732 psi/ft (Cimarex Energy Company, Walbridge 1H, DFIT Analysis, by R.D. Barree, Barree and Associates, "Barree," Cimarex 1H Walbridge DFIT Analysis.pptx, dated 9 January 2017). Estimated static reservoir pore pressure was 11,295 psi, a gradient of 0.98 psi/ft. Fracture extension pressure was 11,895 psi, a fracture extension gradient of 1.017 psi/ft, close to the overburden (lithostatic) gradient (Barree, 2017, note for slide 4) and fracture closure pressure was 11,397 psi, a fracture closure gradient of 0.99 psi/ft. Estimated system permeability from fracture closure time was 230 nD. Barree, however, made important qualifications in the footnotes to their report in three places:

> **ISIP Determination:** ...The ISIP estimate is 6424 psi at surface, or 11695 psi BH. This gives a fracture extension gradient of 1.017 psi/ft, which is very close to overburden gradient. The induced fracture may have bedding-parallel components or near-horizontal structures.
>
> **Linear Flow Plot:** The linear flow extrapolation gives a pore pressure estimate of 11295 psi, or 0.98 psi/ft. If this is correct, there is almost no net stress in the reservoir. Under these conditions it is difficult to generate a conventional tensile hydraulic fracture. Almost all failure in the rock will be dominated by shear, and is expected to follow weak planes, such as bedding and joints.
>
> **DFIT Results:** …With such a high indicated pore pressure, and low net stress, the entire system may not respond as a hydraulic fracture, making the analysis results doubtful.

As a check on the note to Slide 4 (above), lithostatic pressure in the Bruin 1 Walbridge well was calculated from the formation density log (see Lucier et al., 2006, equation 3). Lithostatic pressure at the

DFIT depth of 14,496 ft TVD was 13,196 psi, or a lithostatic gradient of 1.147 psi/ft, not ‘very close’ to the fracture extension gradient but certainly close to it. Barree (above) suggests that fractures developed during the DFIT were more likely horizontal that vertical. Photographs of Rogersville cores from the Chesapeake LAW 1 Northup well (Figure 4–5) show partings between laminae in the cores but no fractures.

The Bruin 1 Walbridge was completed with a 27-stage slickwater hydraulic fracturing treatment using 301,239 BW and 12,113,340 pounds of sand. Analyses of the water used for the fracture treatment shows that 23 of the 27 stages were hydraulically fractured with fresh water averaging 593 ppm total dissolved solids (TDS), two stages were treated using saline water averaging 2635 ppm TDS, and one stage each were treated with highly saline water of 98,462 ppm TDS and 134,182 ppm TDS, respectively (Table 1). Other than the two stages treated with highly saline waters, salinity of the treatment waters, likely from a nearby creek, were insufficient to prevent swelling of freshwater-sensitive expandable clays during the Rogersville fracture treatments (see Bowersox and Shore, 1990).

Post-hydraulic fracture treatment production from the Bruin 1H Walbridge was monitored from 19 February to 28 April 2017. Cumulative production during this period totaled 1416 BO, 54,169 mcfg, and 169,571 BW (Figure 7). Total water recovered during the production was 56.2% of the water injected during hydraulic fracture treatment. The Bruin 1H Walbridge was shut in on 28 April 2017 and subsequently plugged and abandoned.

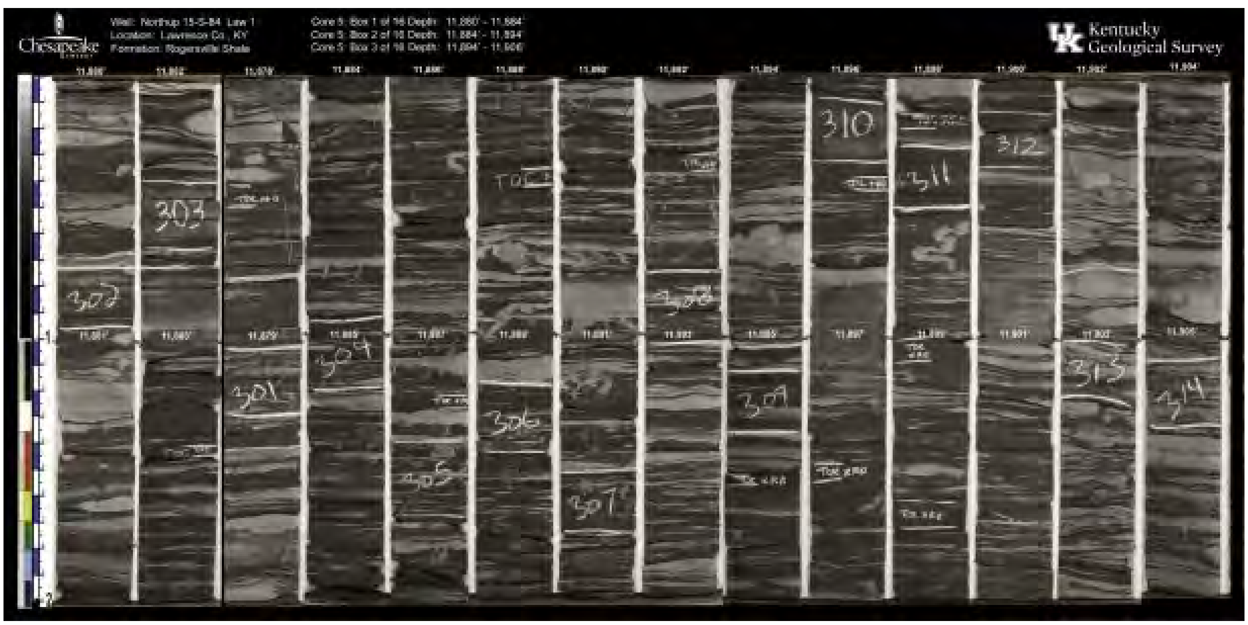


Figure 6. *Cores from the Rogersville “High-TOC” interval in the Chesapeake LAW 1 Northup well, the completion interval in the four wells tested in the Rogersville play (see also Task 7.10). Although shale partings are visible in the section, no fractures are visible other than those from handling the core boxes.*

<u>Bruin Exploration 1 Sylvia Young</u>

Although a robust dataset of geophysical log and core analyses from the Bruin Exploration 1 Sylvia Young was provided to KGS, a limited dataset of operational data was included by the operator. The

Bruin Exploration 1 Sylvia Young ("Bruin 1 Young") was drilled to 12,169 ft in May 2014 and hydraulic-fracture completed in the Rogersville as a vertical well through perforations at 10,468–10,570 ft (Sylvia Young No 1 PVT report.pdf; Given as 10,468–11,044 ft in the Kentucky completion report, Affidavit of Well Log and Completion Report). Of these two completion intervals, the former at 10,468–10,570, 102 ft, is more likely because of its correspondence to the "High-TOC" interval in the well (see Subtask 7.10, Figure 4). Average permeability of 14 crushed core analysis samples from the completion interval from was 1.41 µD. Cuttings from the Bruin 1 Young well were tested for freshwater sensitivity by Stim-Lab Inc. (Core Lab) prior to hydraulic fracturing. A Capillary Suction Test was performed on cuttings from the completion interval at 10,468–10,570 ft and found the cuttings to be moderately sensitive to fresh water (Figure 8).

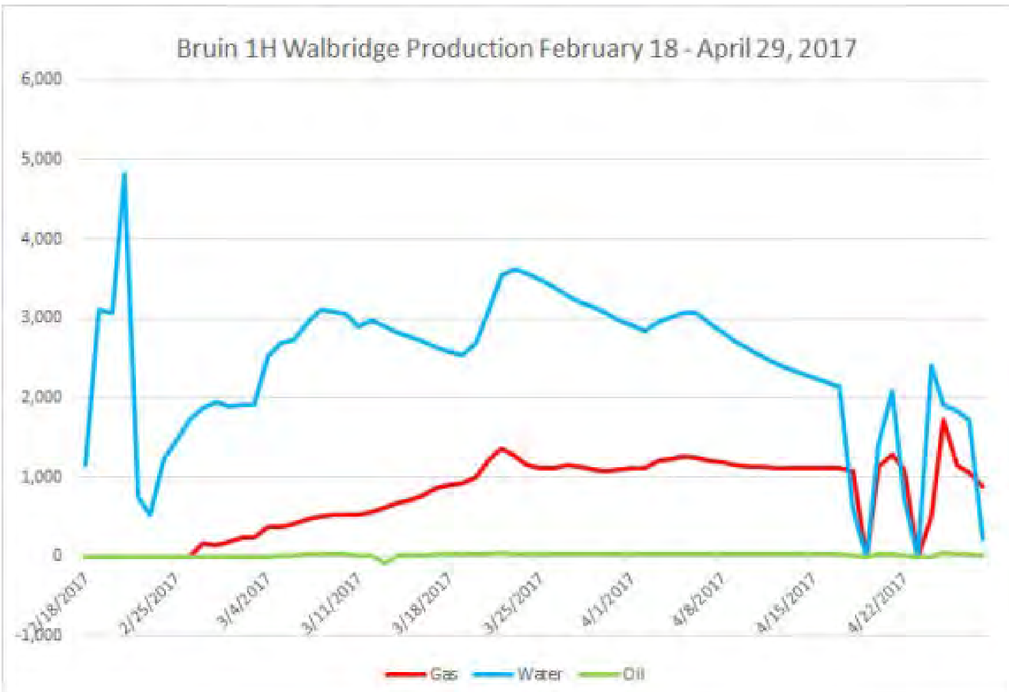


Figure 7. *Bruin 1H Walbridge production test. Average daily production during the test was 35 BOPD of gas condensate, 1321 Mcfgpd, and 4136 BWPD. At the conclusion of the test the well had only produced back 56.2% of the water from the fracture treatment.*

Table 1. *Analyses of waters used in the hydraulic fracture treatment of the Bruin 1H Walbridge well.*

Source Water Analysis of Clean Stage Samples
Cimarex Energy, Walbridge 1H

	Stage	1	2	3	4	5	6	7	8	9	10
Sodium	(Na)	50.95	55.94	53.75	54.87	54.8	69.44	55.82	57.05	85.48	59.8
Calcium	(Ca)	42.65	42.81	45.94	46.66	45.95	46.82	45.41	46.42	47.23	44.5
Magnesium	(Mg)	27.16	27.19	28.84	29.72	29.55	30.21	29.71	30.16	28.15	28.88
Potassium	(K)	7.21	7.05	11.47	7.07	15.92	9.95	7.04	7.6	7.71	7.35
Iron	(Fe)	0.37	0.32	4.48	0.35	0.43	0.5	0.34	0.33	0.31	0.4
Barium	(Ba)	0.12	0.12	0.12	0.1	0.11	0.12	0.11	0.11	0.13	0.12
Manganese	(Mn)	0.05	0.04	0.08	0.02	0.02	0.05	0.02	0.02	0.02	0.05
Strontium	(Sr)	0.62	0.59	0.65	0.61	0.66	0.68	0.65	0.66	0.64	0.62
Chloride	(Cl)	138.96	149.59	164.78	153.14	141.09	153.14	107.06	171.06	167.32	141.09
Bicarbonate	(HCO_3)	79.91	63.44	90.89	79.91	79.91	211.06	60.39	104.31	96.21	89.06
Carbonate	(CO_3)	0	0	0	0	0	0	0	0	0	0
Hydroxyl	(OH)	0	0	0	0	0	0	0	0	0	0
Sulfate	(SO4)	295.83	222.61	212.3	223.88	270.28	388.34	324.09	309.41	287.47	303.49
	TDS	643	569	613	596	638	910	630	727	722	675
	pH	7.97	7.94	7.67	7.91	7.78	7.56	7.84	7.9	7.97	7.94

	Stage	11	12	13	14	15	16	17	18	19	20
Sodium	(Na)	48,718.27	66.25	796.51	57.51	57.05	780.7	53.46	50.58	59.48	56.97
Calcium	(Ca)	88.59	59.05	219.75	55.24	52.68	59.22	37.31	46.48	56.96	55.28
Magnesium	(Mg)	24.69	27.78	47.41	27.04	25.53	28.13	18.56	23.08	28.77	27.86
Potassium	(K)	410	11.68	29.79	9.26	11.3	15.79	7.77	8.34	9.45	8.32
Iron	(Fe)	0.93	0.41	5.26	0.67	0.42	0.29	0.3	0.54	0.65	0.26
Barium	(Ba)	0.56	0.16	0.18	0.15	0.15	0.17	0.12	0.15	0.16	0.14
Manganese	(Mn)	0.06	0.03	0.26	0.04	0.03	0.07	0.02	0.04	0.09	0.02
Strontium	(Sr)	0.98	0.76	10.65	0.66	0.63	0.73	0.47	0.58	0.71	0.63
Chloride	(Cl)	84,643.69	139.53	1497.41	112.31	114.15	1415.73	119.67	102.1	128.77	117.69
Bicarbonate	(HCO_3)	110.41	75.64	67.71	49.41	81.74	40.26	95.16	61.61	79.91	79.91
Carbonate	(CO_3)	0	0	0	0	0	0	0	0	0	0
Hydroxyl	(OH)	0	0	0	0	0	0	0	0	0	0
Sulfate	(SO4)	184.37	217.47	148.78	152.35	156.61	115.85	315.24	211.64	174.78	172.02
	TDS	134,182	598	2,813	464	500	2,456	648	505	537	519
	pH	7.29	7.44	7.41	7.26	7.32	7.11	7.29	7.48	7.01	7.34

	Stage	21	22	23	24	25	26	27
Sodium	(Na)	57.55	35,961.19	94.92	60.48	56.94	59.88	58.82
Calcium	(Ca)	56.27	107.84	53.69	56.2	51.68	57.58	54.13
Magnesium	(Mg)	28.02	30.59	26.13	27.74	25.7	28.65	27.91
Potassium	(K)	9.47	314.96	11.48	8.68	10.11	10.43	9.29
Iron	(Fe)	0.28	1.62	0.37	0.44	0.3	0.34	0.31
Barium	(Ba)	0.14	0.96	0.13	0.12	0.12	0.14	0.12
Manganese	(Mn)	0.02	0.13	0.02	0.04	0.02	0.02	0.01
Strontium	(Sr)	0.86	1.14	0.65	0.61	0.62	0.68	0.62
Chloride	(Cl)	117.69	61,624.80	197.81	117.76	112.31	128.33	116.21
Bicarbonate	(HCO_3)	57.34	76.66	79.91	67.71	60.39	62.96	70.76
Carbonate	(CO_3)	0	0	0	0	0	0	0
Hydroxyl	(OH)	0	0	0	0	0	0	0
Sulfate	(SO4)	189.78	143.03	145.91	154.48	162.25	158.73	165.72
	TDS	517	98,462	610	494	480	527	523
	pH	7.49	7.01	7.51	7.5	7.28	7.3	7.53

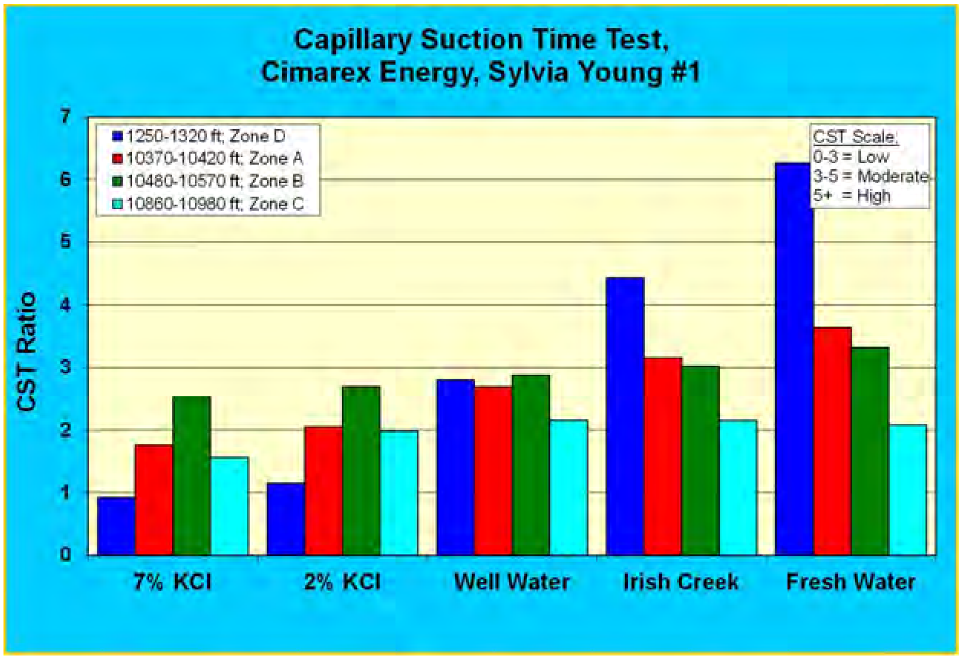


Figure 8. *Capillary Suction Time test on drill cuttings from the Bruin 1 Young well. Zone B is the interval completed in the well. A low to moderate sensitivity was observed to both well water and Irish Creek fracture treatment source waters (Notes for slide 4, Fluid Sensitivity and Shale Stability Report for Cimarex Energy, Multiple Zones, Sylvia Young #1, Lawrence County, KY, 11067. Fluid Sensitivity and Shale Stability in Sylvia Young #1.pptx).*

The Bruin Exploration 1 Sylvia Young was hydraulically fractured, likely using fresh water with 7% KCl as the proppant carrier, before 20 March 2014 when the well was placed in operation (Affidavit of Well Log and Completion Report). The treatment given on the completion report was a "slickwater frac" using 16,113 barrels of fluid and 598,509 pounds of sand, or 5868 pounds per foot of treated interval. A first-stage separator oil and gas sample was collected for PVT analysis on 14 April 2014 by Fesco Ltd., petroleum engineers, Denver, Colorado. At that time the well was produced at a rate of 255 Mcfgpd and 43 bbl of 65.4° API gravity gas condensate. Separator volume factor was 1.122 separator barrels of oil per stock tank barrel of oil. The Rogersville reservoir pressure during the test was 7800 psig, and the reservoir proved to be a retrograde gas-condensate reservoir with a dew point 4252 psig. Initial production on 6 May 2014 was given on the Kentucky completion report as a non-commercial rate of 19 BOPD and 115 Mcfgpd against a backpressure of 200 psi. Shut-in pressure after 24 hrs was 2559 psi. The last information on the completion report is that the Bruin 1 Young was temporarily abandoned on 30 May 2014.

Chesapeake LAW 1 J.H. Northup Estate

The Chesapeake LAW 1 J.H. Northup Estate well, Lawrence County, Kentucky ("Chesapeake 1 Northup"), spud on 29 June 2015 and was drilled as a vertical test well to 15,950 ft TD where 5½-inch casing was cemented at 15,936 ft on 04 September 2015 after 79 days of drilling. An extensive dataset of geophysical logs, cores and core photographs (see Figures 4–5, above), cuttings, core analyses, and geochemical analyses were collected from the Chesapeake 1 Northup and donated to KGS. The Rogersville "High-TOC" interval was penetrated in the well at 11,872–11,992 ft. Core photographs from the Chesapeake 1 Northup well show the Rogersville “High-TOC” interval to be alternating beds of dense dark gray shale and well-cemented very fine-grain sandstone to siltstone (Figure 5). A DFIT was conducted on 19 August 2017 that measured in situ pore pressure in the Rogersville at 11,889–11,890 ft. Static reservoir pressure was 11,514 psi and static reservoir temperature was 165°F. The Chesapeake 1 Northup well was re-entered, perforated on 20 November 2017, and the Rogersville hydraulically fractured the next day. No fracture treatment information was given in the daily operations reports. The Rogersville was production tested from 27 November 2017 to 14 December 2017 (FESCO Production Test Report: Chesapeake Energy Northup-Client Data.xlsx). No oil or gas production was reported for the well during this period although three gas chromatography reports dated 5–7 December 2017 show produced dry gas with heating values averaging 1130 BTU/cf. The well was shut-in on 31 December 2017 and the Rogersville section abandoned by 9 February 2018. The Chesapeake 1 Northup was temporarily abandoned on 28 September 2018 and plugged and abandoned and wellsite remediated on 21 December 2019. Abandonment of the Chesapeake 1 Northup effectively condemned the entire Rogersville play.

Horizontal Technology Energy Company 572360 Winston Caudill

The Horizontal Technology Energy Company 572360 Winston Caudill, Johnson County, Kentucky (“Horizontal Technology 572360 Caudill” well), was drilled to a total depth of 10,765 ft MD, 10,741 ft TVD, then redrilled horizontally beginning from a kick-off point at 9571 ft MD to a total drilled depth of 13,383 ft, 10,838 ft TVD, 2461 ft S25.75°E from its surface location. It was completed with 5½-inch casing cemented at 13,172 ft. A robust dataset of logs, core analyses and photos (Figure 8) was collected from the well to guide its completion. It was perforated in the Rogersville “High-TOC” interval (Figure 2) in 15 stages from 11,207–13,116 ft MD (10,842–10,905 ft TVD) for production from the Rogersville before 29 July 2015. No production data was provided by the operator as part of their donation although the Kentucky Division of Oil & Gas shows no oil or gas production for the well in 2015 and the well is absent from the list of wells’ production in 2016. A record of formations penetrated by the well filed with the Kentucky Division of Oil & Gas dated 12 March 2018 suggests that it was abandoned by then.

Discussion and Conclusions

The Rogersville play failed primarily because of the low mobile hydrocarbon saturation of the in the strata (see Subtask 7.10), extremely low permeability in the µD to nD range, lack of a natural fracture system (Figures 5 and 8), high fresh water-sensitive expandable clay content (Figure 4), reservoir pore and fracture pressures approaching lithostatic pressure (see the discussion of the Bruin 1 Walbridge well, above), and hydraulic fracturing the wells using fresh water as the proppant-carrying fluid (Figures 5 and 7; Table 1). An additional hurdle in the Rogersville play was that average OOIP (as gas-equivalent) in the three Rogersville wells analyzed in Subtask 7.10, Cimarex (operating as Bruin Exploration) 1 Young and 1 Walbridge wells and the Chesapeake 1 Northup well, was a sparse 6520 BOE per acre (equivalent barrels of oil to convert gas in place to equivalent barrels of oil).

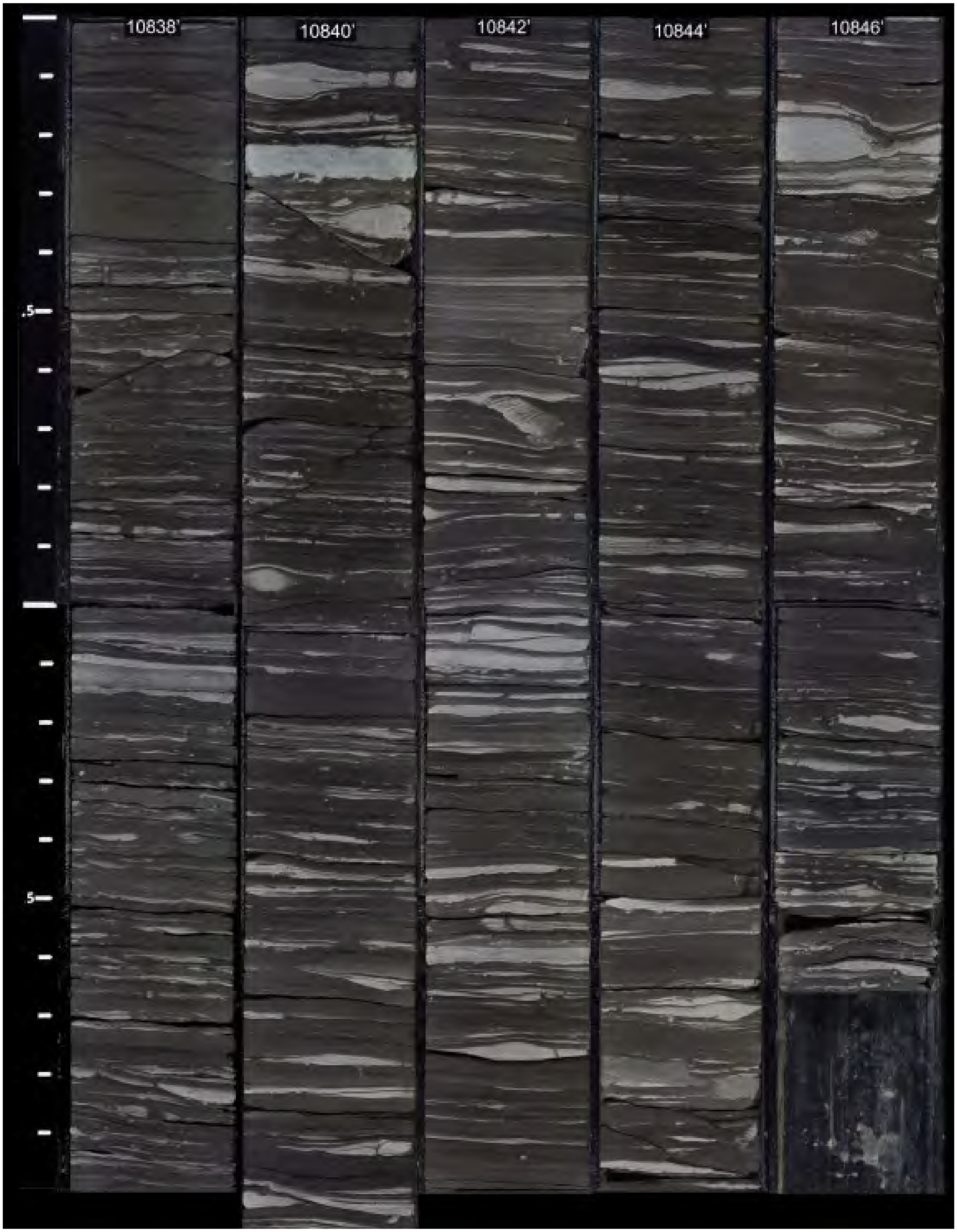


Figure 9. *Cores from immediately above the completion interval in the EQT 572360 Caudill well show rare natural fracturing in the Rogersville at 10,838.2–10,838.7 ft, 10,840.2–10,840.9 ft, and 10,845.8–10,846.0 ft offsetting beds in the rock. All depths are TVD. Partings between beds were likely caused during handling and shipping the cores to KGS.*

The Bruin 1 Walbridge and Horizontal Technologies 572360 Caudill wells were drilled and completed as multi-stage horizontal wells. By the standard of current Marcellus Shale or Permian Basin development, these wells are short-reach horizontal wells having, ~3100-foot reach (Caudill well) and ~4300-foot reach (Walbridge well). Review of the well location plats submitted to the Kentucky Division of Oil & Gas with their well permit applications, both wells, when completed with multi-stage hydraulic fractures, suggests they were designed to develop slightly less than 50 acres of Rogersville reservoir with about 316.3 MBOE in place. The Walbridge well was hydraulically fractured in 27 stages targeting the "High-TOC" interval of interest in the wellbore (Figure 2). Average production during the 22-day well test was a non-commercial 33 BOPD (50° API gravity condensate), 1145 Mcfgpd, and 3290 BWPD (file Walbridge production data.xlsx). The Walbridge well was subsequently plugged and abandoned.

The petrophysical log evaluation model used to evaluate the three wells of Subtask 7.10 was built to evaluate vertical fractured Monterey Shale wells in the San Joaquin Basin, Central California, with a productive reservoir interval 850 ft thick at an average depth of 2880 ft. In comparison to the Rogersville wells, these Monterey Shale wells averaged ~1.05 MM BOIP. Decline curve analysis of the Monterey Shale wells showed average per-well recoveries of ~15% of OOIP, or 150 MBO per well. Assuming similar performance from the horizontal Rogersville wells, expected resources would average a non-commercial 47.4 MBOE per Rogersville well. If the Rogersville reservoir could be developed with long-reach, >10,000 ft horizontal well to develop 160 acres, average developed oil in place resources would be ~1 MMBOE. Assuming, then, an average recovery of 15% of OOIP, developed reserves would be ~150 thousand barrels per well. Considering all of the other issues in developing the Rogersville outlined above, however, the play has been condemned and no additional exploration of it could be recommended.

Acknowledgements

This research was funded by the U.S. Department of Energy, award number DE-FE0031783. Our DOE Program Manager was Robert Vagnetti, to whom we offer our thanks for their guidance during the project. Well data and information used to complete this evaluation was provided by Cimarex Energy Company, EQT Corporation, Cabot Oil & Gas Corporation, Chesapeake Appalachia, LLC, and Hay Exploration, Inc. Our thanks to all of these operators whose contributions made this evaluation possible.

References

Bowersox, J.R., and Shore, R.A., 1990, Reservoir compaction of the Belridge diatomite and surface subsidence, South Belridge field, Kern County, California, in Kuespert, J.G., and Reid, S.A., eds., Structure, Stratigraphy and Hydrocarbon Occurrences of the San Joaquin Basin: Society of Economic Paleontologists and Mineralogists and American Association of Petroleum Geologists, Pacific Sections, p. 225-230.

Bowersox, J.R., Greb, S.F., Zhu, J., and Harris, D.C., 2021, Geomechanical properties will constrain CO_2 injection into the Lower Ordovician Rose Run Sandstone deep saline reservoir, Appalachian Basin, Kentucky, U.S.A.: Journal of Rock Mechanics and Geotechnical Engineering, 14 p., https://doi.org/10.1016/j.jrmge.2021.04.010

Lucier, A., and Zoback, M., 2008, Assessing the economic feasibility of regional deep saline aquifer CO_2 injection and storage: a geomechanics-based workflow applied to the Rose Run sandstone in eastern Ohio, USA: International Journal of Greenhouse Gas Control, vol. 2, p. 230–247.

d. Task 4.2 - Machine learning analysis of previous completions*

By Shahab Mohaghegh, PhD

West Virginia University – Department of Petroleum and Natural Gas Engineering

Morgantown, WVa.

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 6 months of work out of the budgeted 18-month research plan.)

Task Objectives

The main objective of this subtask is to use Shale Analytics to design completion practices for the Rogersville Shale. Shale Analytics is the collection of state-of-the-art data-driven techniques including artificial intelligence, machine learning, and data mining that attempts to increase the production efficiency of a shale plays. Shale Analytics is a complete departure from traditional approaches to modeling. In this new paradigm, field measurements are substituted for the physics of production and geology as the foundation for the model. This characteristic makes it a superior alternative for modeling shale assets, where the physics of hydrocarbon production are not well understood. In this new approach, instead of imposing our understanding of the flow mechanism, the impact of multi-stage hydraulic fractures, and the production process on the reservoir model, we allow the production history, well log, completion and hydraulic fracturing data to guide our model and determine its behavior.

The uniqueness of this technology is that it incorporates "hard data" directly into the model, so that the model can be used to optimize the hydraulic fracture process. The "hard data" refers to field measurements during the hydraulic fracturing process such as fluid and proppant type and amount, injection pressure and rate, as well as proppant concentration. This novel approach contrasts with traditional practices which focus on the use of non-measurable, interpretive or "soft data" such as frack length, width, height and conductivity in reservoir models.

We have access to a very detailed, proprietary data set that includes formation, completion, hydraulic fracturing implementation, operational condition, and production data from hundreds of shale wells in the Appalachian and Permian basins. While such data cannot be released and shared with the public, the knowledge that can be extracted and learned from the data can be used to guide us to design the most effective completion for the Rogersville Shale. Knowledge extraction from these proprietary data will be accomplished through Artificial Intelligence and Machine Learning through a process called "Transfer Learning".

Engineering Application of AI & Machine Learning

Learning includes two sides: the educator and the educatee. At the university, the educator is the professor and the educatee is the student. In the context of application of Artificial Intelligence and Machine Learning in upstream oil and gas industry, the educator must be a Petroleum Data Analytics expert while the educatees are a series of open computer algorithms.

Learning is defined as “the acquisition of knowledge and skill through experience, study, or by being taught.” When it comes to engineering related tasks, humans learn by attending universities, taking classes and earning relevant Bachelor, Masters and PhD degrees, followed by gaining experience through working in the field. When “machines” (computer algorithms) supposed to learn, they also need to go through substantial amount of teaching that in the context of AI is called training.

Effective teaching at educational institutes requires the educator or the teacher to have two major characteristics: (a) to be highly knowledgeable on the topic and, (b) to have strong communication skills. The teacher in the educational institute teaches humans that speak natural language and are required to have certain prior knowledge. For example, the junior and senior petroleum-engineering students at West Virginia University speak and understand English and have completed the pre-requisite courses such as advanced calculus, thermodynamics, and fluid mechanics (to name a few). When the educatee is a machine (open computer algorithm such as neural networks), it does not speak or understand natural language and does not have any prior knowledge related to advanced calculus, thermodynamics, and fluid mechanics.

In this case, the domain expertise of the educator must be communicated with the computer algorithm not through natural language, but through data. Therefore, when it comes to Machine Learning, the educator must have gained specific type of communication skills and expertise with open computer algorithms that makes her/him capable of using the data in a proper fashion in order to be able to teach the computer algorithm the type of physics-based expertise that are required for problem solving and decision making.

Transfer Learning

Since Machine Learning is a data-driven technology, it requires considerable amount of data for the open computer algorithms to learn. “Transfer Learning” is a Machine Learning related technology with the objective of taking advantage of the knowledge gained from a series of available data from a given task and then to use the gained knowledge in order to solve a reasonably similar problem that does not include the required amount of data for a comprehensive learning process.

For this project the idea is to transfer the learned knowledge from existing shale assets in Marcellus and Utica into Rogersville shale, in order to optimize completion and production of the new wells that are planned to be drilled and completed in this shale formation.

Data Summary

Data associated with more than 750 wells from two shale reservoirs (Marcellus Shale and Utica Shale) have been received. The data includes an average of 50 variables (field measurements) for each well. The field measurements included in the data sets belong to following categories: Well Characteristics, Formation Characteristics, Completion Design Parameters, Hydraulic Fracture Implementation, Operational Conditions, and Production.

In this part of the report details about the two data sets from Marcellus Shale and Utica Shale are presented as well as examples of the quality and the quantity of the data that will be used for this project.

<u>Introduction</u>

The first step in this subtask is to receive the available data and identify how much of the available data can be used for the purposes of this subtask and prepare the data for Shale Descriptive Analytics.

These two data sets include one from Marcellus shale that included 400 wells, each well including 59 field measurements and one from Utica shale that included 355 wells, each well including 73 field measurements. Both these data sets include 6 different categories of field measurements.

These categories are:

Category 1: Well Characteristics,

Category 2: Formation Characteristics,

Category 3: Completion Design Parameters,

Category 4: Hydraulic Fracture Implementation,

Category 5: Operational Conditions, and

Category 6: Production

Table 1. *Number of Field Measurement for Each Category, Marcellus Shale*

Category of Field Measurements	Number oParameters
Well Characteristics	7
Formation Characteristics	16
Completion Design Parameters	6
Hydraulic Fracture Implementation	9
Operational Conditions	9
Production	12
Total	59

***Table 2**. List of Field Measurements for each Category - Marcellus Shale*

Well Characteristics	Hydraulic Fracture Implementation
W-East-m (Lat.)	S-Avg. Maximum Pressure (psi)
W-North-m (Long.)	S-Avg. Injection Pressure (psi)
W-Inclination	S-Avg. Maximum Injection Rate (bbls/min)
W-Azimuth	S-Avg. Injection Rate (bbls/min)
W-Deviation Type	S-CleanVolume (bbls)
W-Measured Depth	S-Slurry Volume (bbls)
W-True Vertical Depth	S-Proppant/Stage (lb)
	S-Total Injected Propant (lbs)
Formation Characteristics	S-Maximum Proppant Concentarion (lbs/gal)
F-Avg. Languir Pressure (psi)	
F-Avg. Langmuir Volume (scf/ton)	**Operational Conditions**
F-Net Thickness (ft.)	P-BTU Area
F-Permeability (md)	P-Soak Time (days)
F-Porosity (%)	P-Start of Production (Date)
F-Initial Water Saturation (%)	P-Avg. WPH-1 Months (psi)
F-Total Organic Carbon (%)	P-Avg. WPH-3 Months (psi)
F-Bulk Mudulus	P-Avg. WPH-6 Months (psi)
F-Minimum Horizontal Stress	P-Avg. WPH-12 Months (psi)
F-Poisson's Ratio	P-Avg. WPH-18 Months (psi)
F-Shear Mudulus	P-Avg. WPH-24 Months (psi)
F-Youngs Modulus	
F-Avg. Frac Gradient	**Production**
F-Avg. Breakdown Pressure (psi)	Rich Gas 1 Month (MCF)
F-Avg Breakdown Rate (bbls/min)	Rich Gas 3 Month (MCF)
F-Avg. ISIP (psi)	Rich Gas 6 Month (MCF)
	Rich Gas 12 Month (MCF)
Completion Design Parameters	Rich Gas 18 Month (MCF)
C-Completion Date	Rich Gas 24 Month (MCF)
C-Cluster Spacing (ft.)	Water 1 Month (bbls)
C-Comp-Stimulated Lateral Length (ft.)	Water 3 Month (bbls)
C-Total Number of Clusters	Water 6 Month (bbls)
C-Total Number of Stages	Water 12 Month (bbls)
C-Shot Density (Shots/ft)	Water 18 Month (bbls)
	Water 24 Month (bbls)

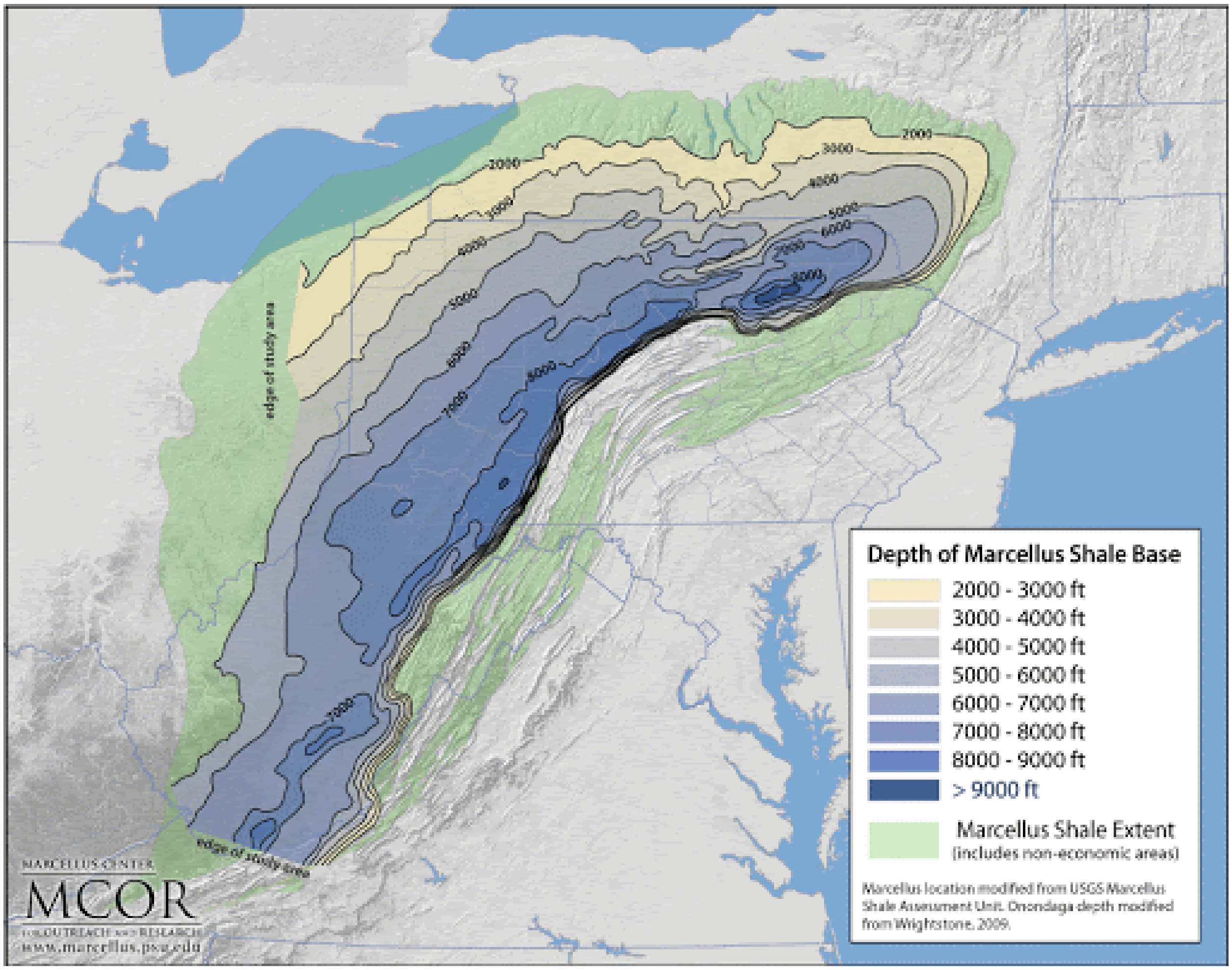


***Figure 1**. Marcellus Shale Depth Contour Map ranging from 2,000 ft. – 9,000 ft.*

Table 1 shows the number of Marcellus shale field measurements that are include in each of the categories mentioned above. Detail list of these field measurements are shown in Figure 1 and Figure 2, display contour maps of Marcellus Shale Depth and Thickness in Pennsylvania, Ohio, and West Virginia.

Table 14 shows the number of Utica shale field measurements that are include in each of the categories mentioned above. Detail list of these field measurements are shown in Table 25. Figure 13 and Figure 24 display contour maps of Utica Shale Depth and Thickness in Pennsylvania, Ohio, and West Virginia.

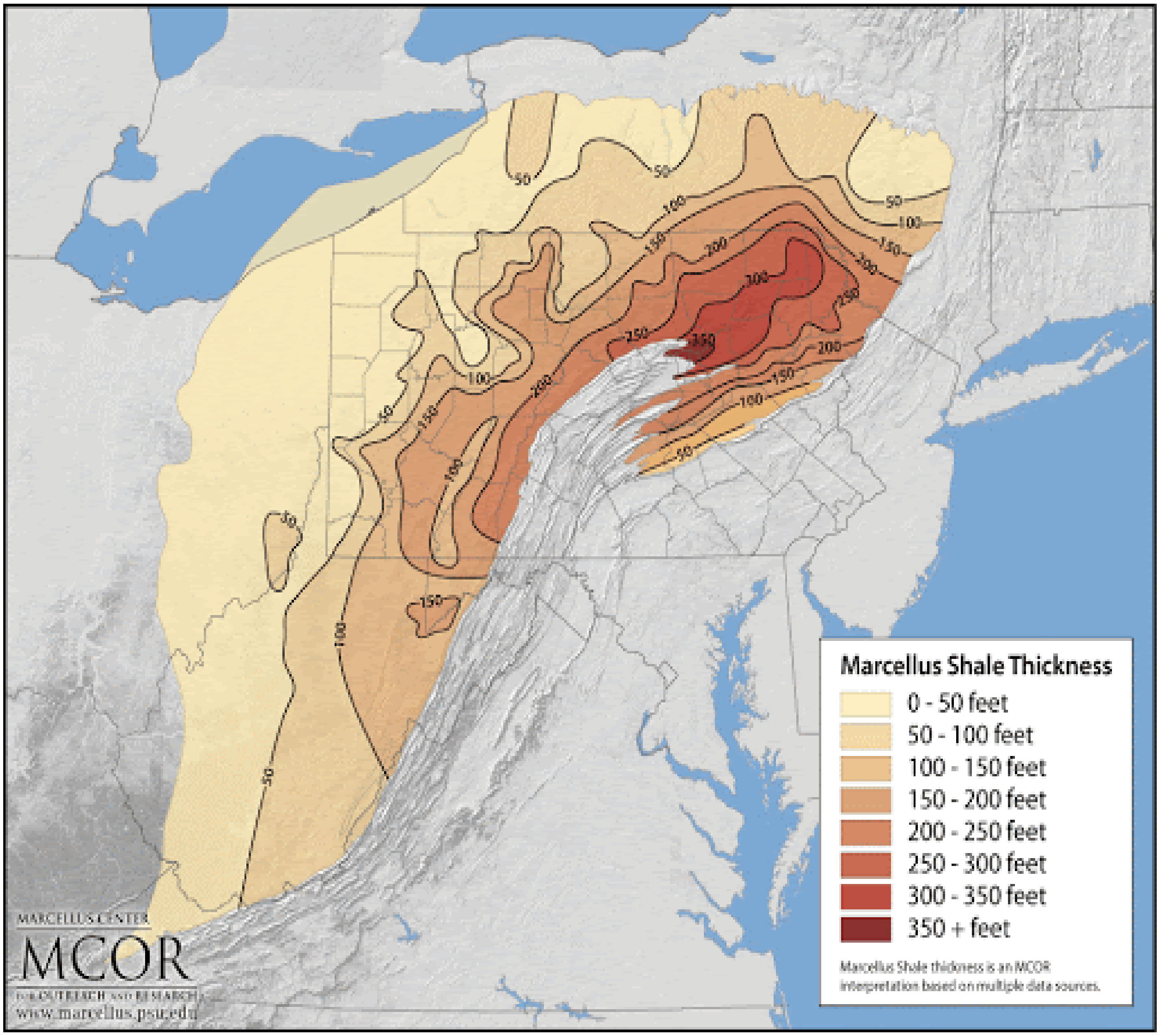


Figure 2. *Marcellus Shale thickness contour map ranging from 0 ft. to higher than 350ft.*

Table 3. Number of Field Measurement for Each Category, Utica Shale

Category of Field Measurements	Number oParameters
Well Characteristics	13
Formation Characteristics	32
Completion Design Parameters	9
Hydraulic Fracture Implementation	11
Operational Conditions	4
Production	4
Total	73

***Table 4**. List of Field Measurements for each Category - Utica Shale*

Well Characteristics	**Formation Characteristics**
W-Pad Drilled Order	F-CGR Zone(BH)
W-Spud (Date)	F-Pre Treat shutin Pressure (psi)
W-Total Depth (Date)	F-Post Treat shutin Pressure (psi)
W-East-m (Lat.) - Surface	F-Breakdown Pressure (psi)
W-North-m (Long.) - Surface	F-Instant Shutin Pressure ISIP (psi)
W-East-m (Lat.) - BH	F- Fractur Thoughness
W-North-m (Long.) - BH	F-Frac Grad (psi-ft)
W-Avg. X	F-NTG (PayFlag)
W-Avg. Y	F-Carbonate VClay
W-Inclination	F-Carbonate VSand
W-Azimuth	F-Carbonate VCarb
W-Measured Depth	F-Carbonate VTOC
W-True Vertical Depth	F-Carbonate VP1
	F-Carbonate VS2
Completion Design Parameters	F-Carbonate GR
C-Lateral Length (ft.)	F-Carbonate Maturity
C-In Target Zone	F-Carbonate Thickness
C- Total Number of Stages	F-Carbonate Nphi
C- Total Number of Perforations	F-Carbonate Temp
C-Min. of Top (ftKB)	F-Carbonate Temp Anomaly
C-Max. of Bottom (ftKB)	F-Carbonate Resistivity
C-Shot Density (Shots/ft.)	F-Carbonate Min Horz Stress
C-Entered Shot Total	F-Carbonate Poission Ratio
C-Completion Date	F-Carbonate Young Modulus
	F-Carbonate Max Depth Burial
Hydraulic Fracture Implementation	F-Carbonate Uplift Magnitude
S-Service Company	F-Carbonate GIPTOT (bcf-section)
S-Frac Type	F-Shale VClay
S-Proppant/Stage (lb/stg)	F-Shale Porosity Logs (Density Log)
S-Avg. Treatment Pressure (psi)	F-Shale SW
S-Maximum Treatment Pressure (psi)	F-Shale VTOC
S-Minimum Treatment Pressure (psi)	F-Shale GIPTOT (bcf-section)
S-Avg. Treatment Rate (bbl/min)	
S-Maximum Treatment Rate (bbl/min)	**Production**
S-Minimum Treatment Rate (bbl/min)	Gas 6 Months (MCF)
S-Clean Volume (bbl/stage)	Oil 6 Months (bbl)
S-Soak Time (days)	Water 6 Months (bbl)
	CGR 6 Months
Operational Conditions	
P-Avg. Tubing Pressure 180 Days (psi)	
P-Avg. Casing Pressure 180 Days (psi)	
P-Avg. Choke Setting 180 Days	
P-Start of Production (Date)	

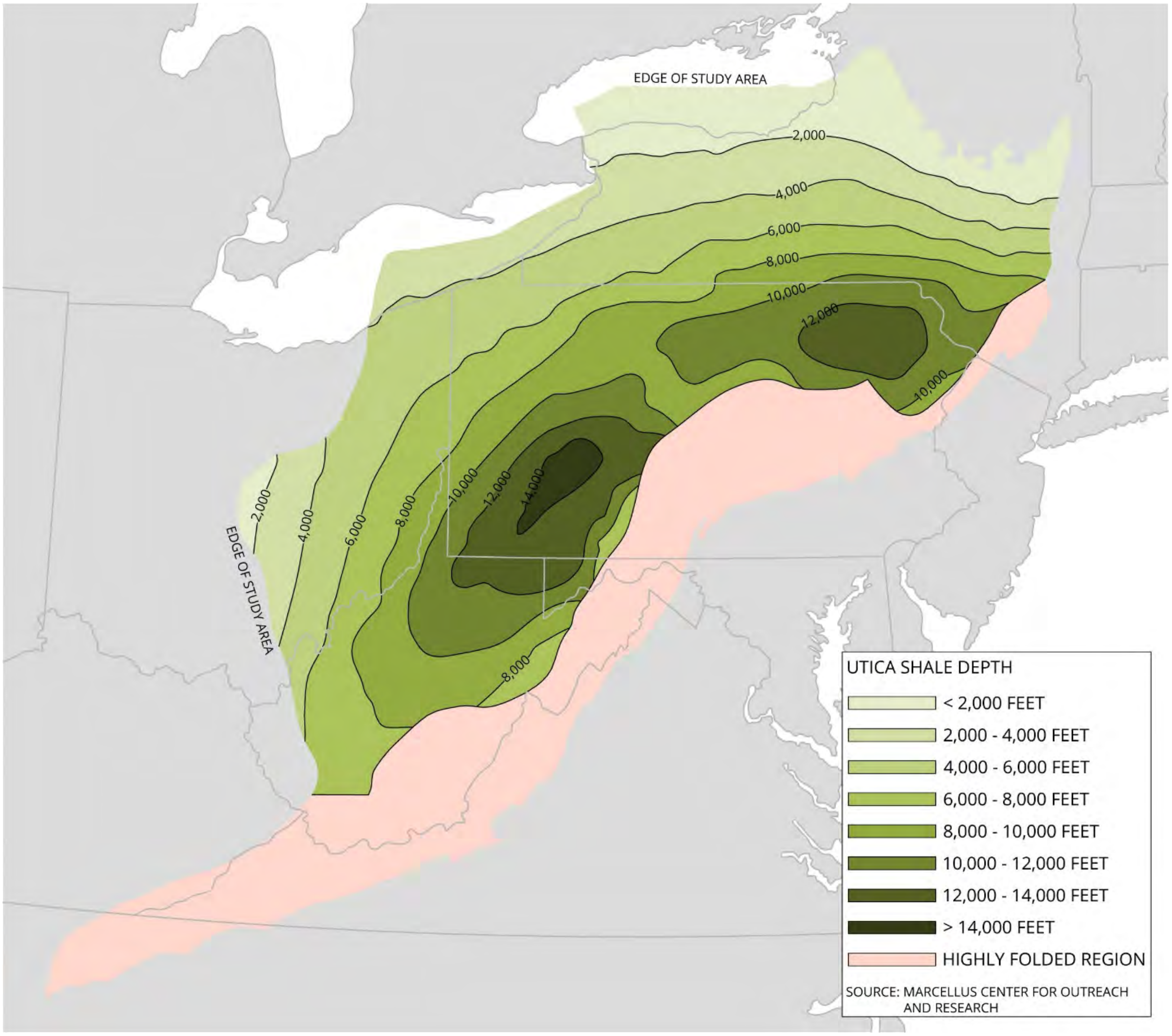


Figure 3*. Utica Shale Depth Contour Map ranging from 2,000 ft. – 14,000 ft.*

<u>Data from Marcellus Shale and Utica Shale</u>

Field measurements of shale wells are very complex. A series of plots of field measurements from these two data sets (Marcellus Shale and Utica Shale) have been generated and included in this report to demonstrate the complexity of the field measurements in both Marcellus Shale and Utica Shale.

Figure 5 demonstrates the relative location of 400 wells in Marcellus Shale. Figure 6 through Figure 10 demonstrate plots of field measurements versus the productivity index of the wells in Marcellus shale. Figure 6 shows two examples of the production characteristics of the 400 Marcellus Shale wells. Figure 7 displays four examples of the well characteristics of the 400 Marcellus Shale wells. Figure 8 demonstrates four examples of the formation/reservoir characteristics of the 400 Marcellus Shale wells. Figure 9 shows four examples of the completion design characteristics of the 400 Marcellus Shale wells, and finally Figure 10 displays four examples of the hydraulic fracture characteristics of the 400 Marcellus Shale wells.

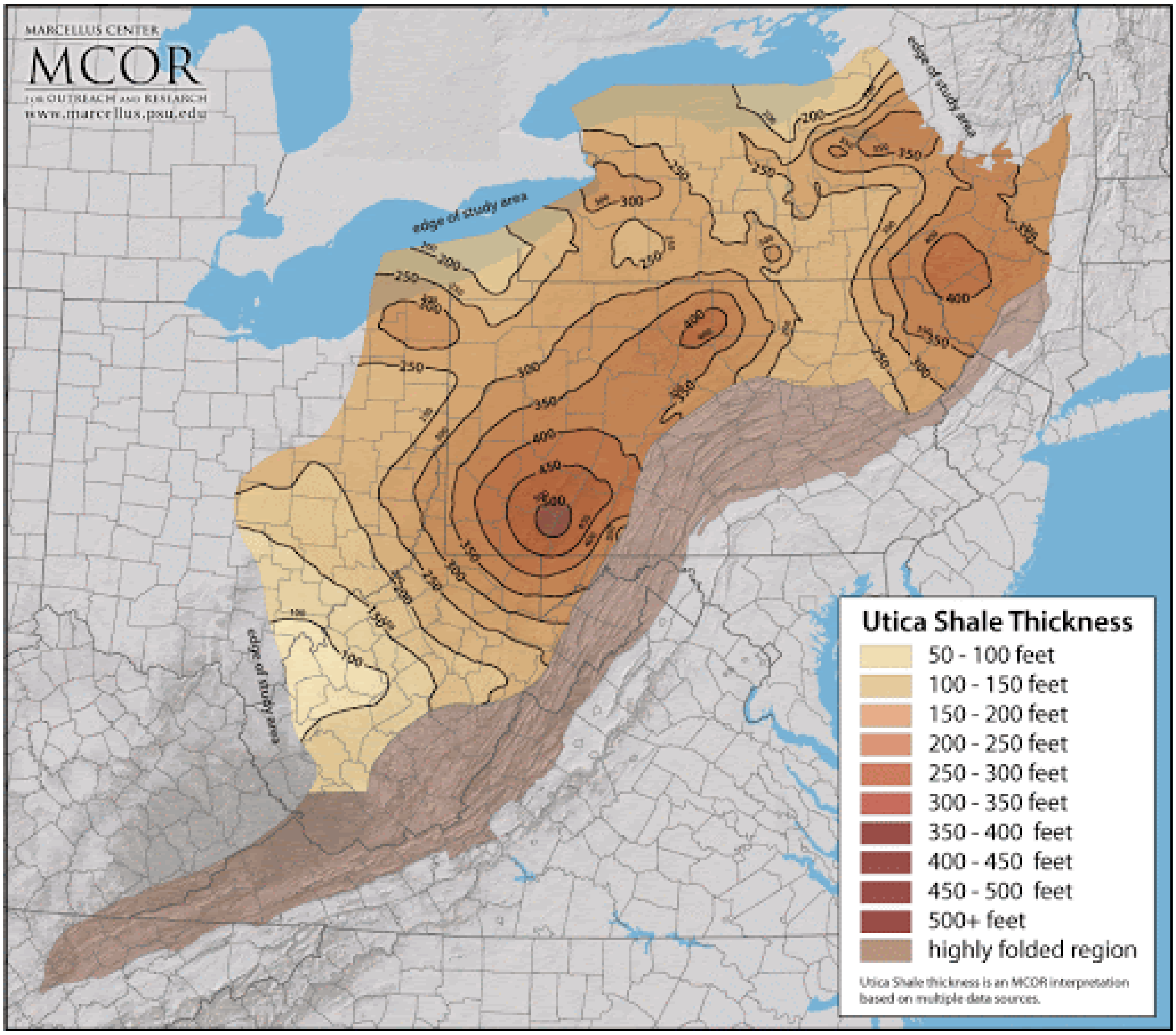


***Figure 4**. Utica Shale thickness contour map ranging from 50 ft. to higher than 500ft.*

Furthermore, Figure 11 demonstrates the relative location of 355 wells in the Utica Shale. Figure 12 through Figure 16 demonstrate plots of field measurements versus the productivity index of the wells in Marcellus shale. Figure 12 shows two examples of the production characteristics of the 355 Utica Shale wells. Figure 13 displays four examples of the well characteristics of the 355 Utica Shale wells. Figure 14 demonstrates four examples of the formation/reservoir characteristics of the 355 Utica Shale wells. Figure 15 shows four examples of the completion design characteristics of the 355 Utica Shale wells, and finally Figure 16 displays four examples of the hydraulic fracture characteristics of the 355 Utica Shale wells.

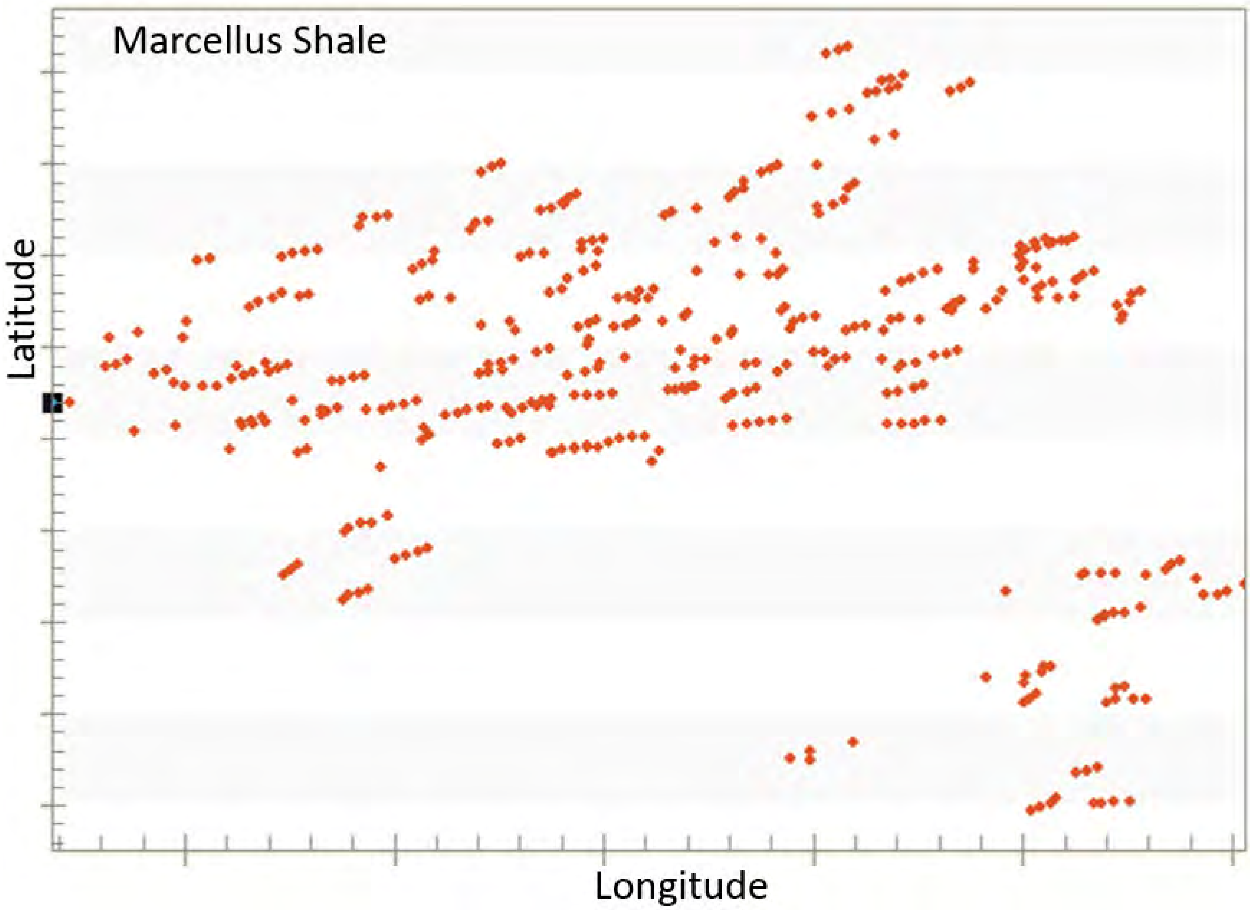


Figure 5. *Well Locations - Marcellus Shale*

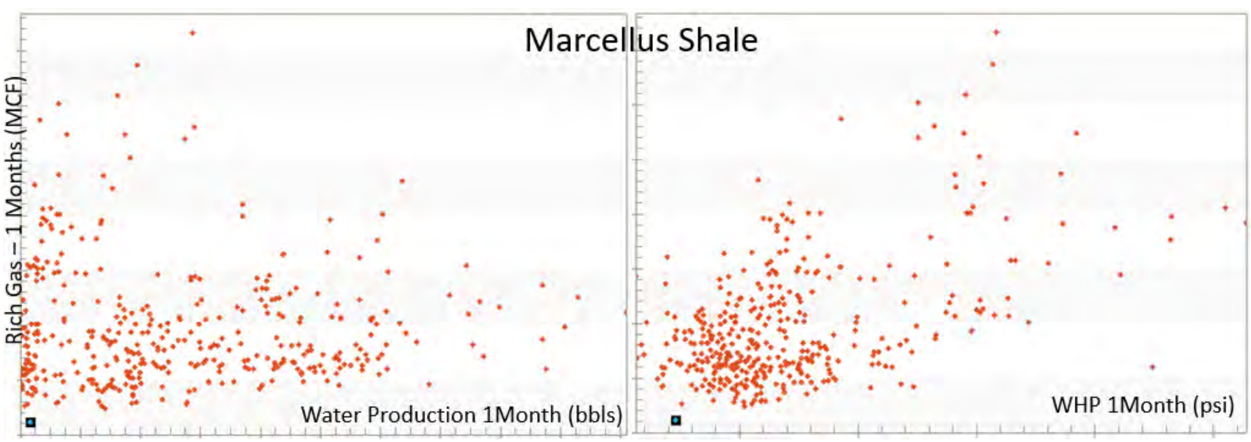


Figure 6. *Production Characteristics - Marcellus Shale*

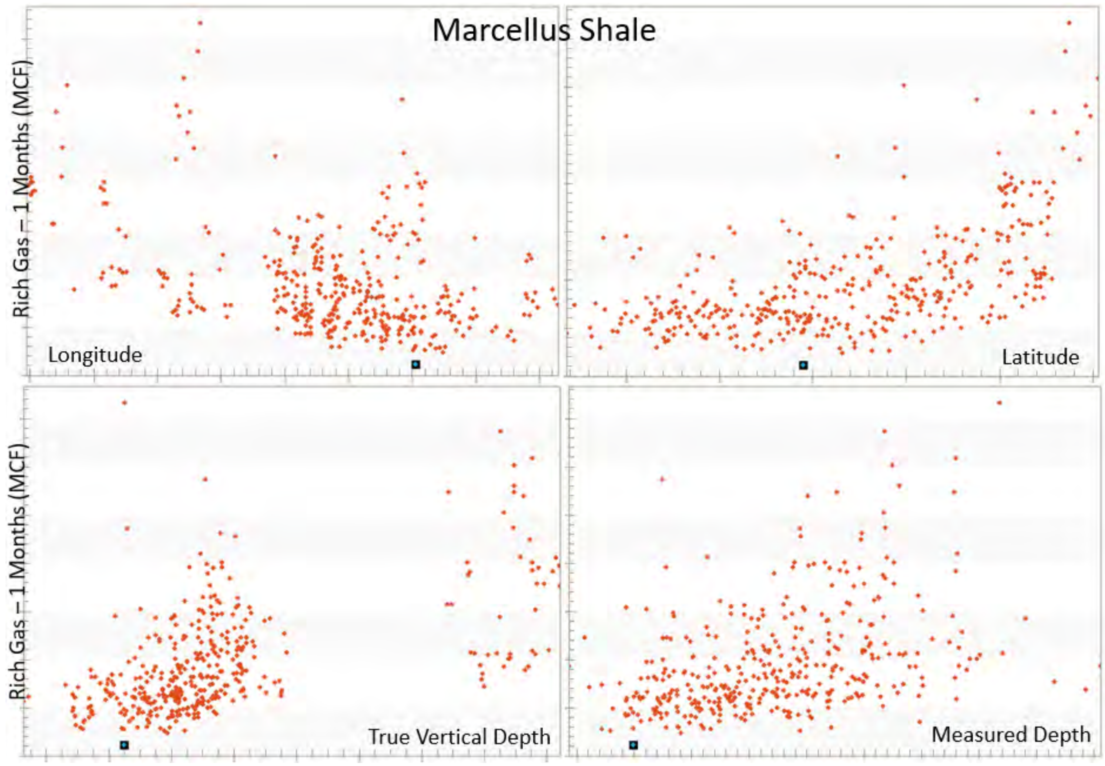


***Figure 7**. Well Characteristics - Marcellus Shale*

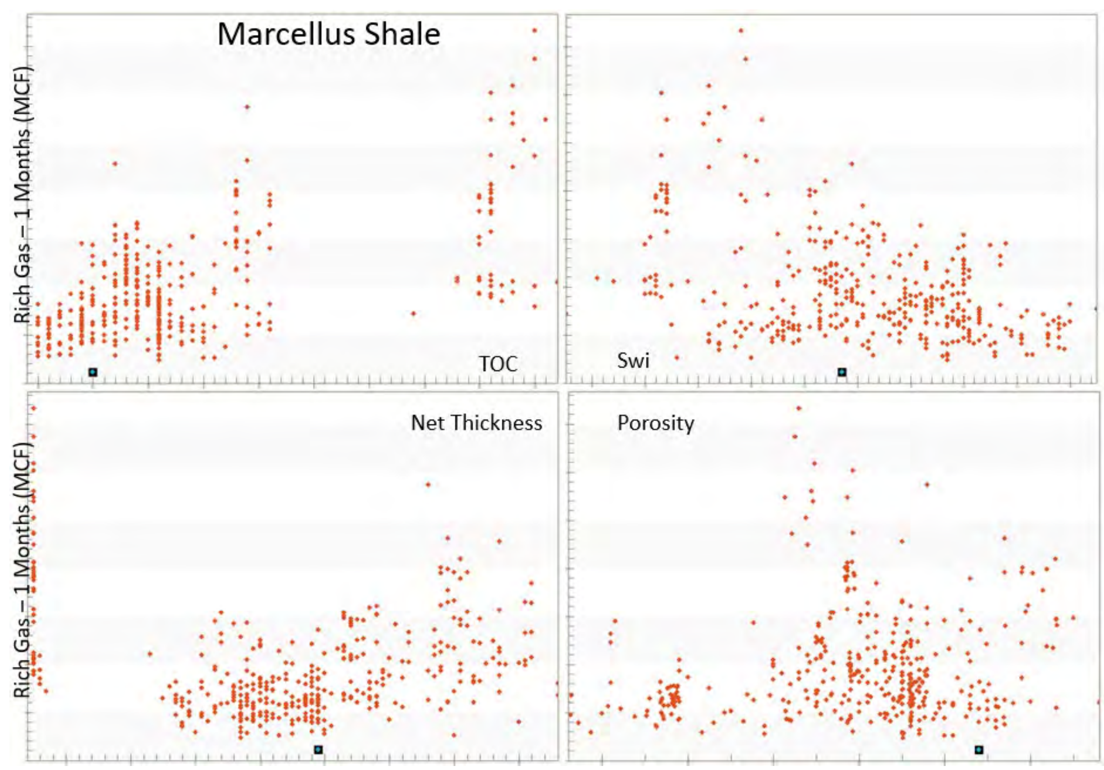


***Figure 8**. Formation Characteristics - Marcellus Shale*

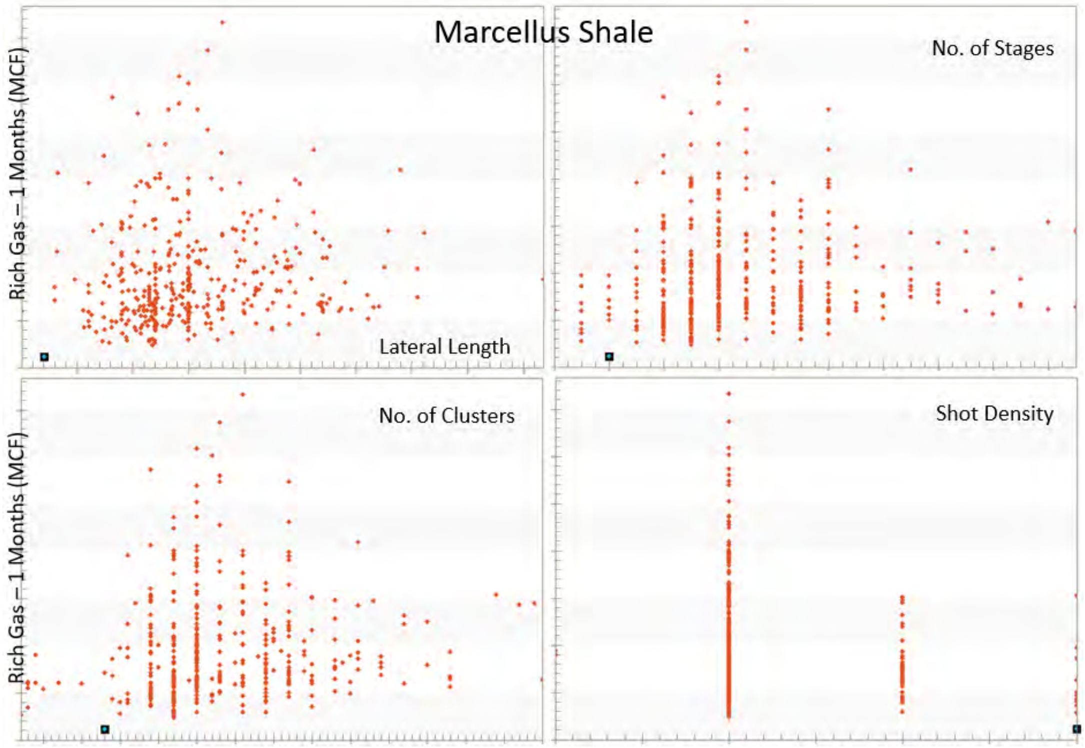


Figure 9. *Completion Characteristics - Marcellus Shale*

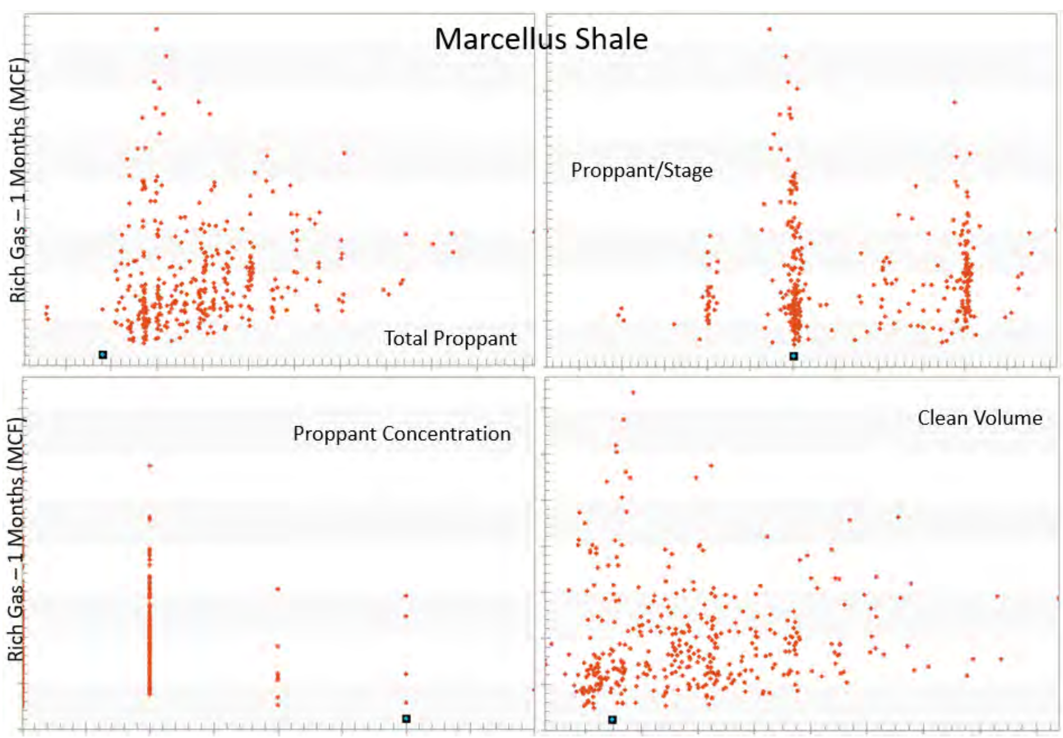


Figure 10. *Hydraulic Fracturing Characteristics - Marcellus Shale*

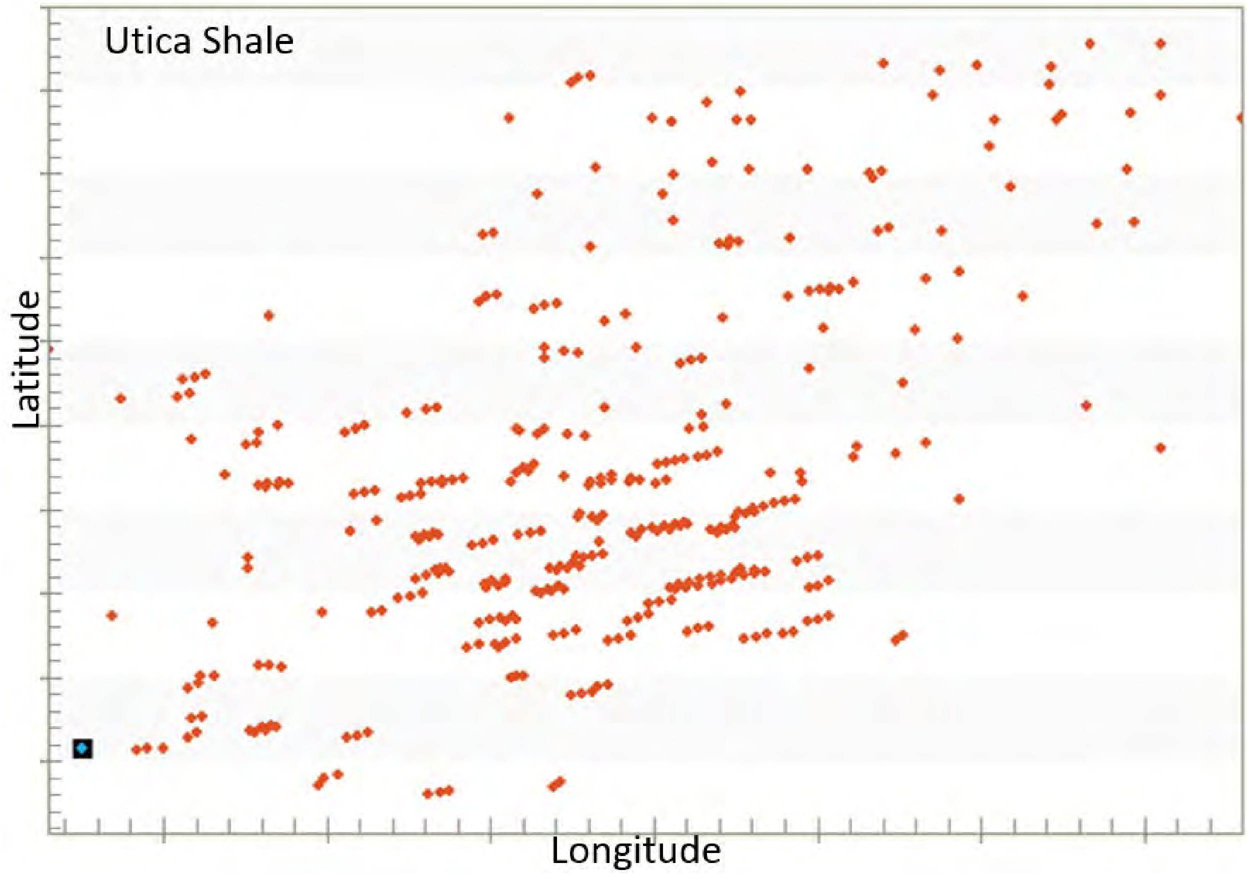


Figure 11. *Well Locations - Utica Shale*

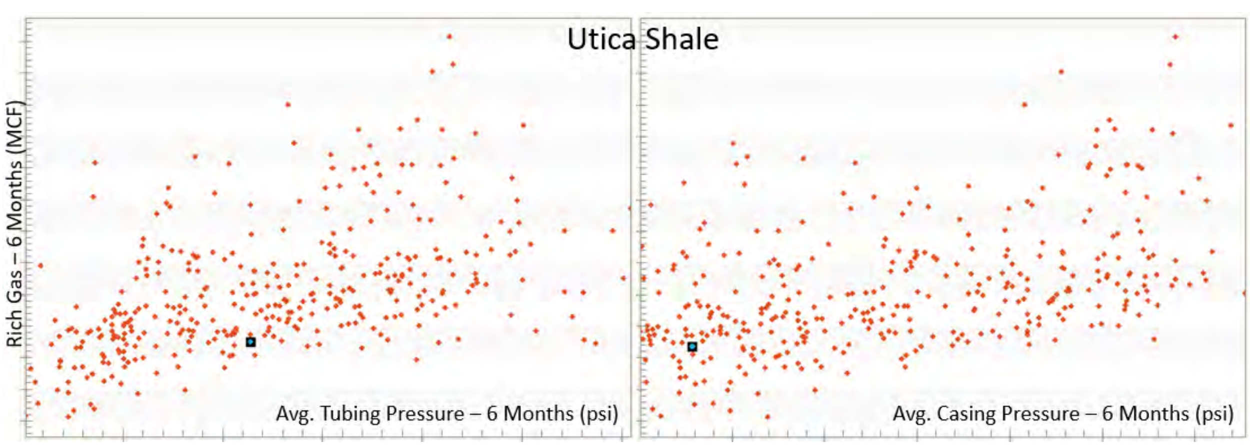


Figure 12. *Production Characteristics - Utica Shale*

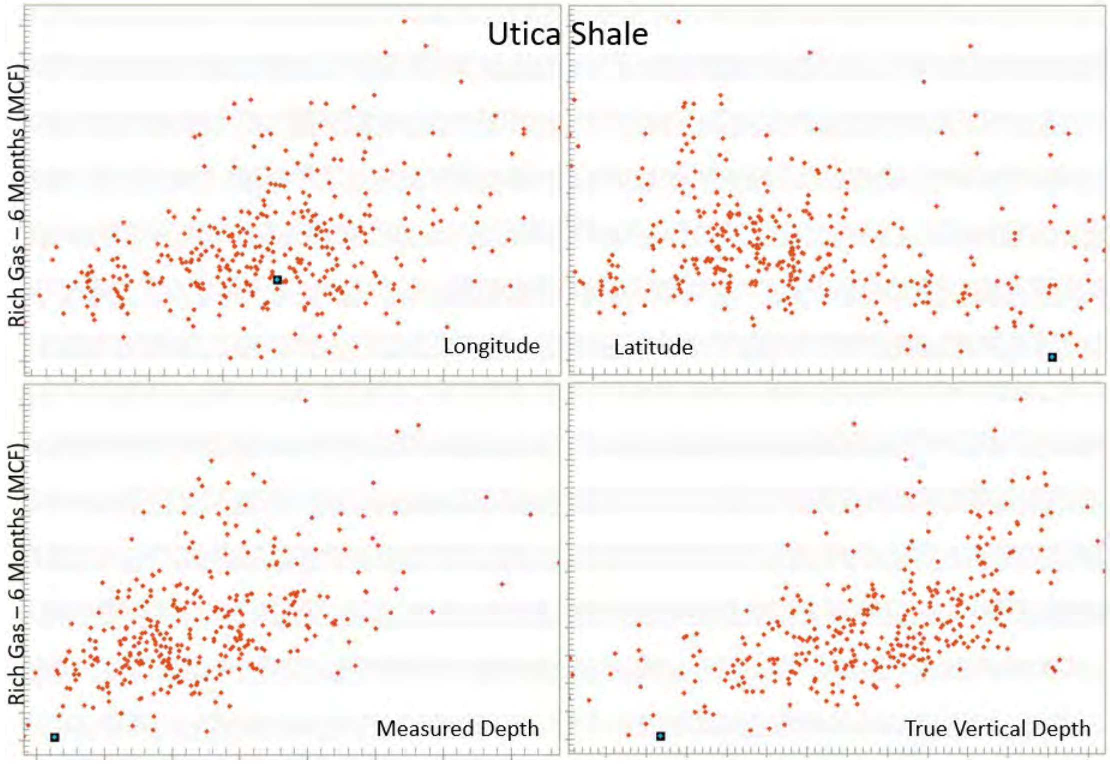


***Figure 13**. Well Characteristics - Utica Shale*

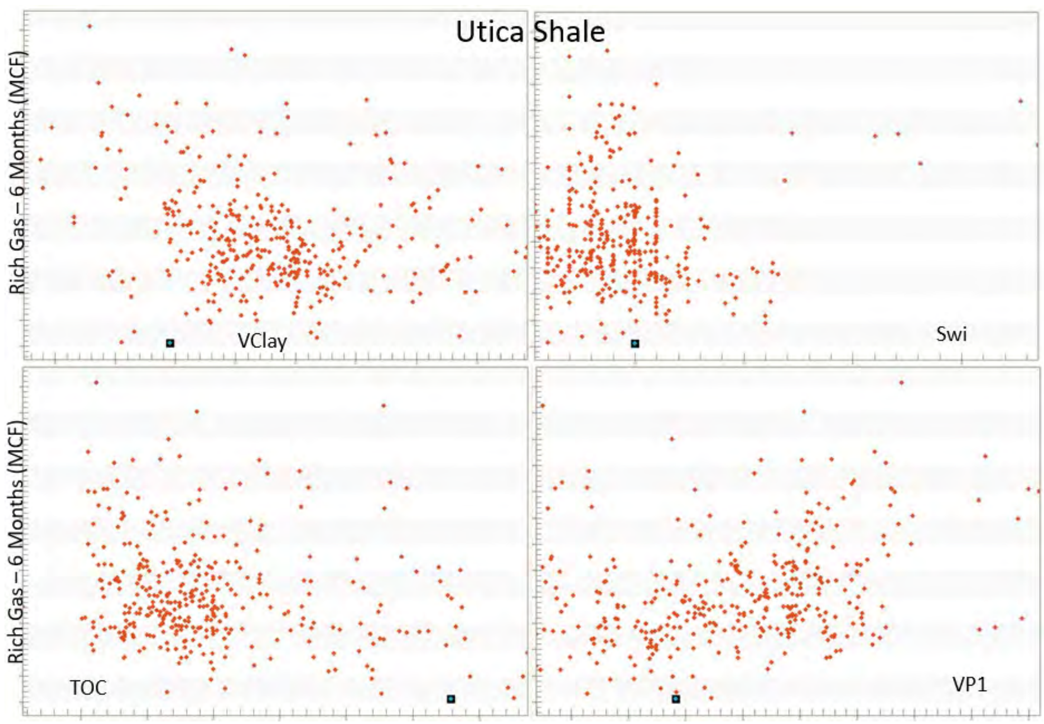


***Figure 14**. Formation Characteristics - Utica Shale*

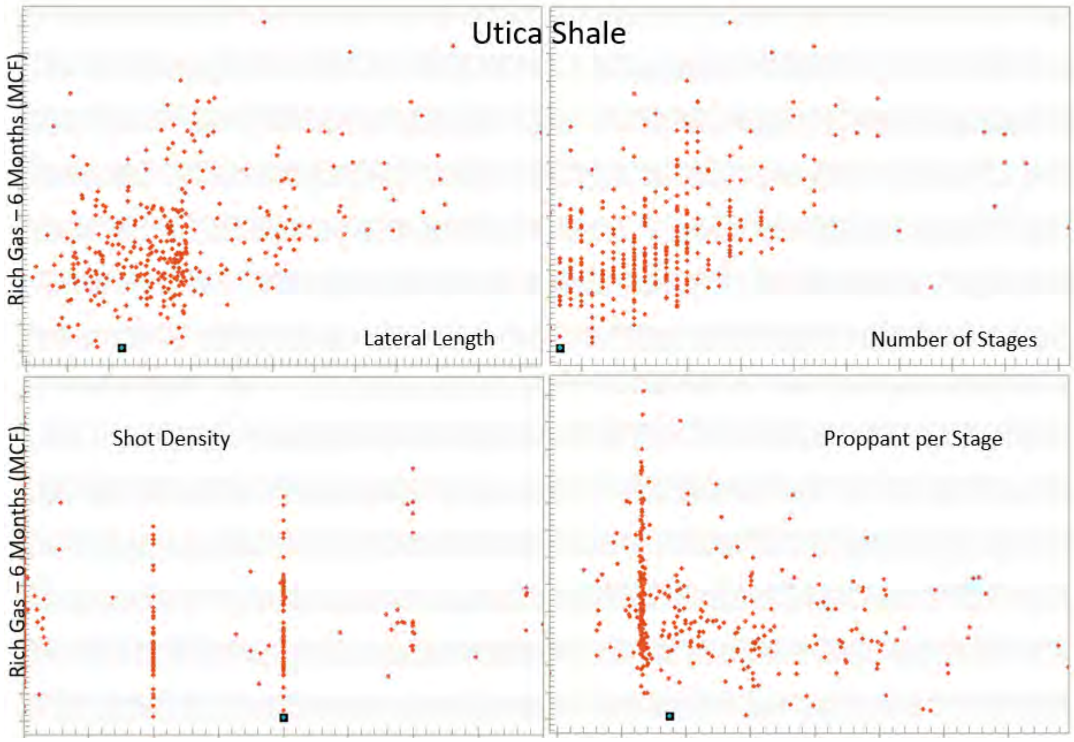


***Figure 15**. Completion Characteristics - Utica Shale*

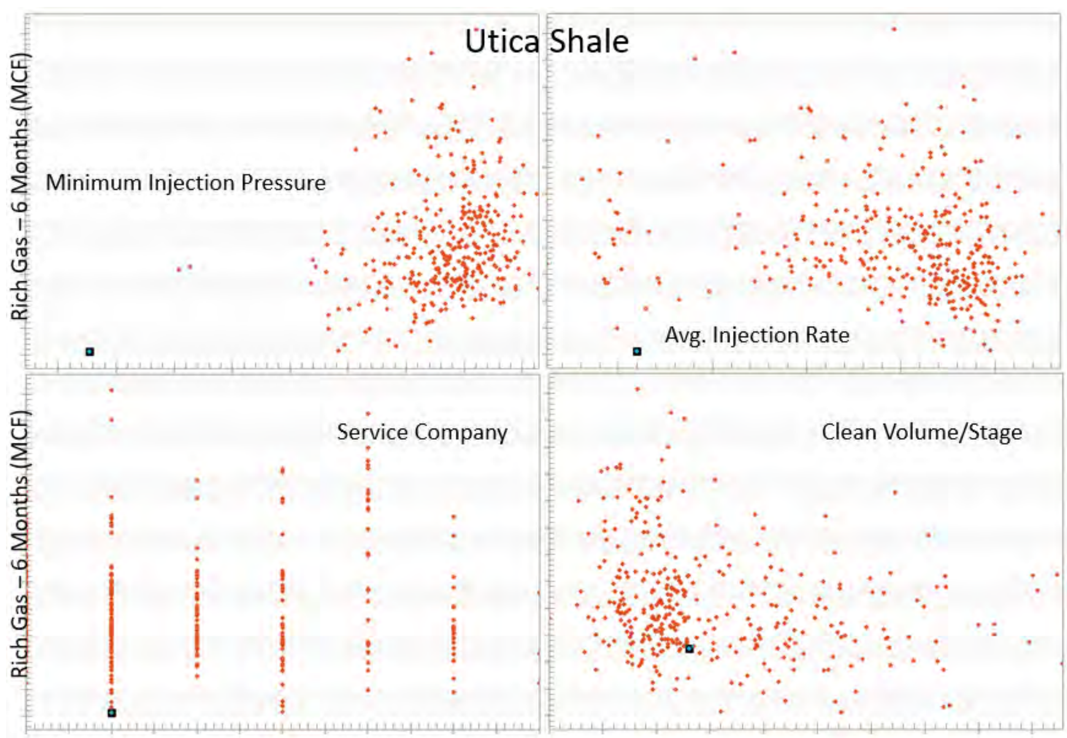


***Figure 16**. Hydraulic Fracture Characteristics - Utica Shale*

Task Outcomes

The Engineering analysis of past unconventional wells involves two separate elements; a “post-mortem” analysis of the six existing unconventional Rogersville Shale wells (by UK), and a Machine Learning analysis of past Utica Shale, Marcellus Shale, and Wolfcamp Shale unconventional oil and gas wells (by WVU-LEADS).

The WVU-LEADS group has compiled the necessary data from multiple assets and is building a comprehensive Shale Analytics data set of relevant variables. After compiling the necessary data from the multiple asset and initial analyses of all the available data, the WVU-LEADS group has concluded that data from about 750 wells from two assets (one in Marcellus and one in Utica) can be used for the Shale Descriptive Analytics for this phase of this project.

The WVU-LEADS group has started the first step of its Shale Descriptive Analytics. In this step Fuzzy Pattern Recognition was performed on data from 400 wells that have been producing from the Marcellus Shale. Fuzzy Pattern Recognition is an implementation of Supervised Fuzzy Cluster Analysis that is combined with an optimization algorithm in order to discover trends and patterns in seemingly chaotic data from shale resources. Fuzzy Pattern Recognition increases the granularity of the Well Quality Analysis. Following figures in this report show the application of Fuzzy Pattern Recognition on 25 different field measurements of 400 Marcellus Shale wells. In each of the figures below, a pattern is discovered of each field measurement (variable) versus 30 days rich gas production.

These Fuzzy Pattern Recognitions shown in the following figures include five different categories of variables that impact production of hydrocarbon from shale wells. These categories are:

1. Well Locations; Two Variables: Latitude, and Longitude- Figure 17
2. Reservoir Characteristics; Twelve Variables: TOC, Initial Water Saturation, Porosity, Youngs Modulus, Shear Modulus, Bulk Modulus, Poisson’s Ratio, Minimum Horizontal Stress, Frac Gradient, Average ISIP, Breakdown Pressure, and Breakdown Rate. Figure 18, Figure 19, and Figure 20
3. Completion Design; Four Variables: Stimulated Lateral Length, Total Number of Stages, Total Number of Clusters, Number of Clusters per Stage - Figure 21
4. Hydraulic Fracturing Implementation; Six Variables: Average Injection Rate, Average Injection Pressure, Clean Volume, Slurry Volume, Total Amount of Proppant, Maximum Proppant Concentrations - Figure 22 and Figure 23
5. Operational Conditions; One Variables: Well-Head Pressure - Figure 24

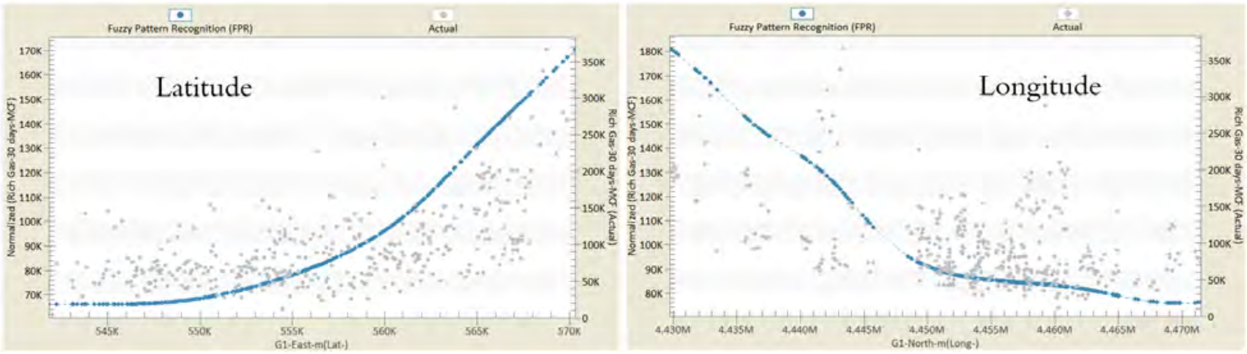


Figure 17. *Fuzzy Pattern Recognition of* ***Well Locations*** *for 400 Marcellus Shale wells.*

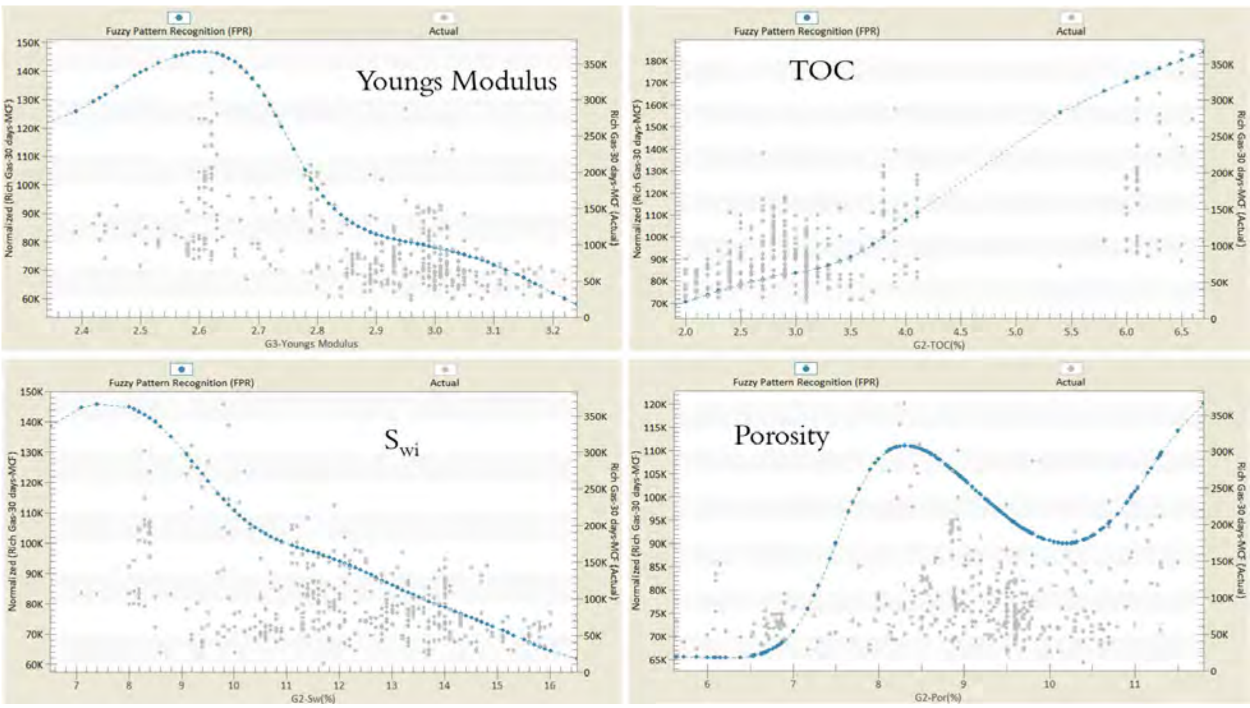


Figure 18. *Fuzzy Pattern Recognition of* ***Reservoir Characteristics*** *for 400 Marcellus Shale wells.*

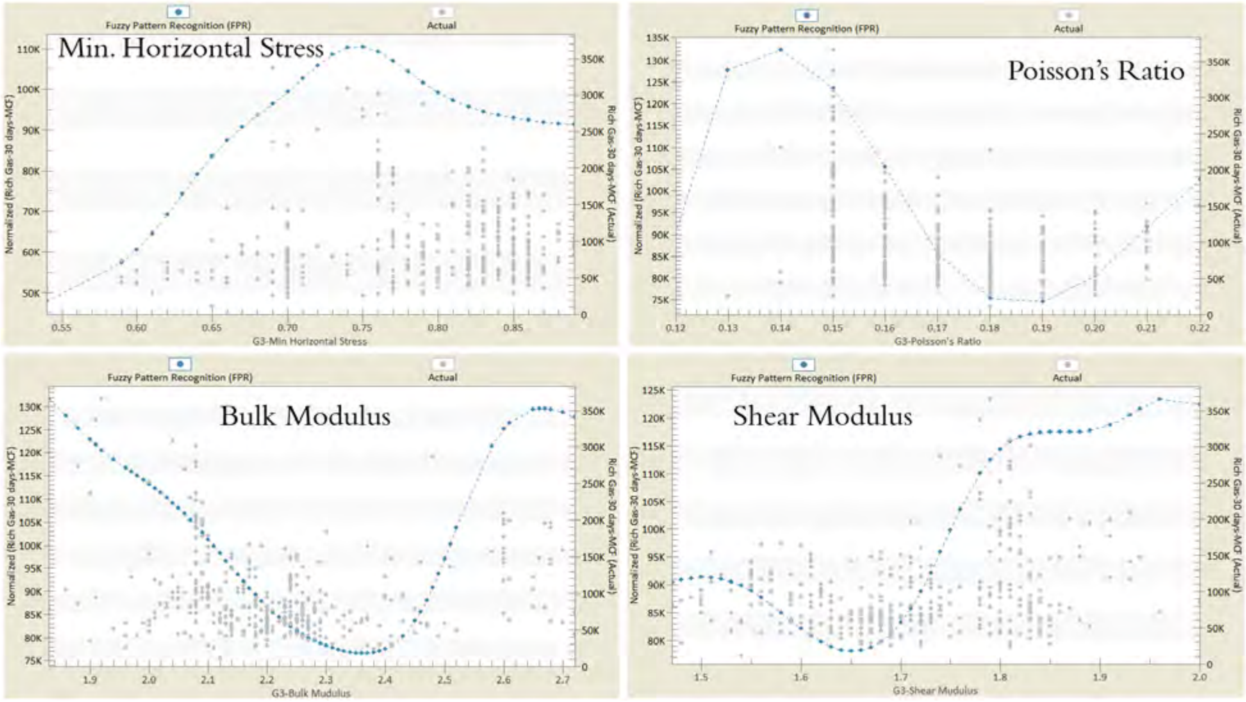


Figure 19*. Fuzzy Pattern Recognition of* ***Reservoir Characteristics*** *for 400 Marcellus Shale wells.*

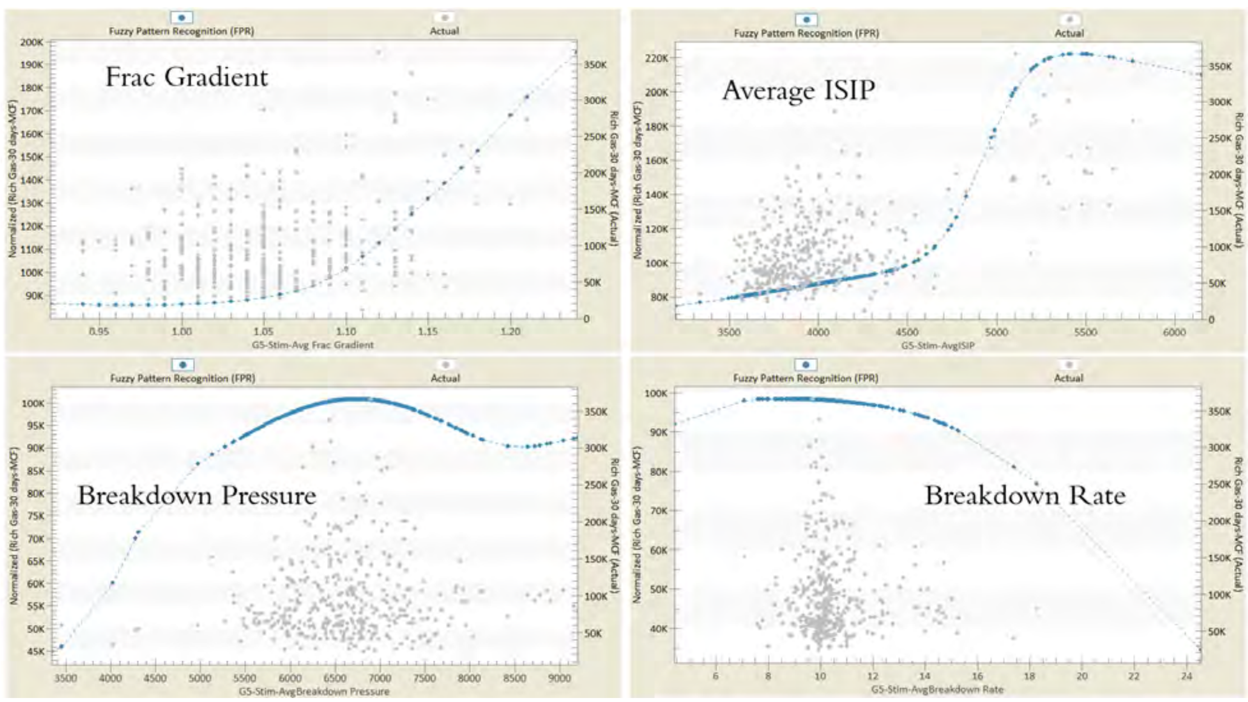


Figure 20*. Fuzzy Pattern Recognition of* ***Reservoir Characteristics*** *for 400 Marcellus Shale wells.*

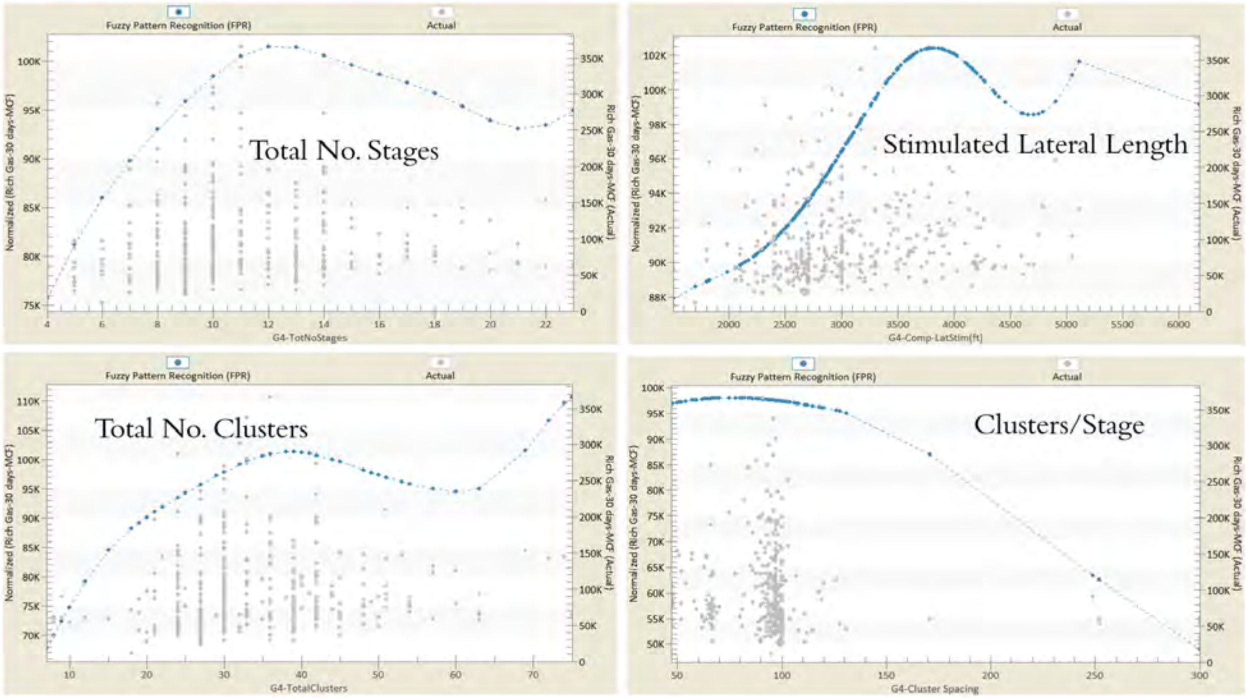


Figure 21*. Fuzzy Pattern Recognition of* ***Completion Design*** *for 400 Marcellus Shale wells.*

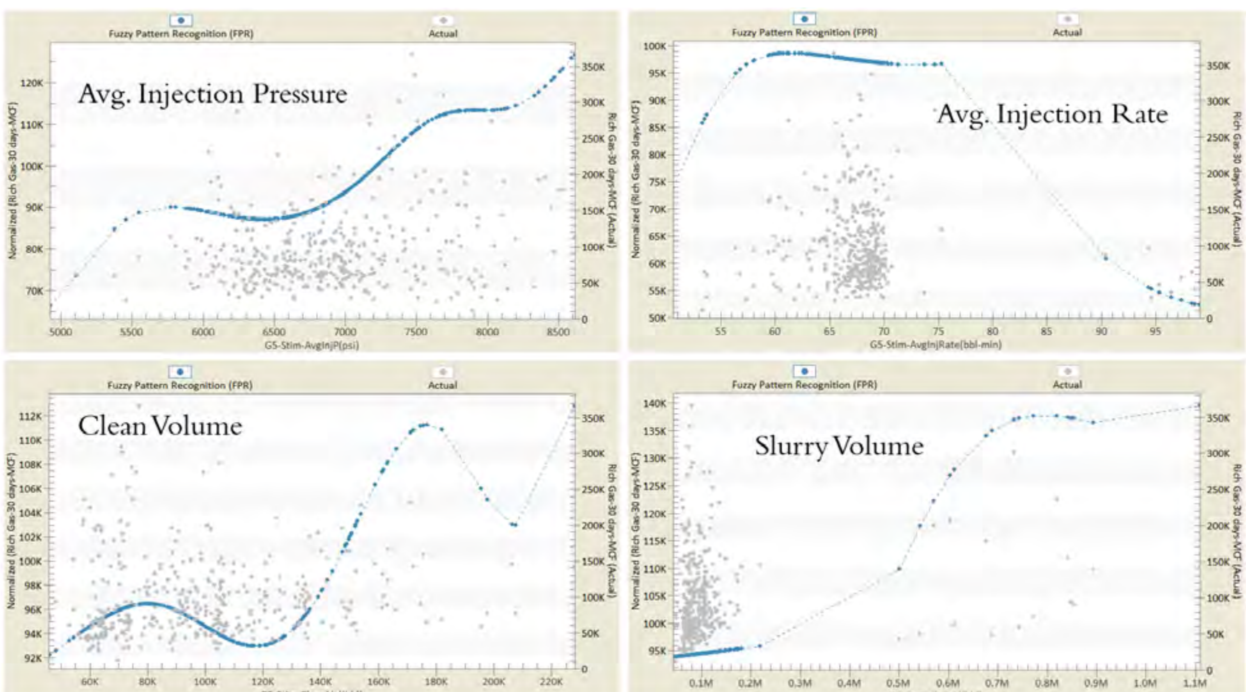


Figure 22*. Fuzzy Pattern Recognition of* ***Hydraulic Fracturing Implementation*** *for 400 Marcellus Shale wells.*

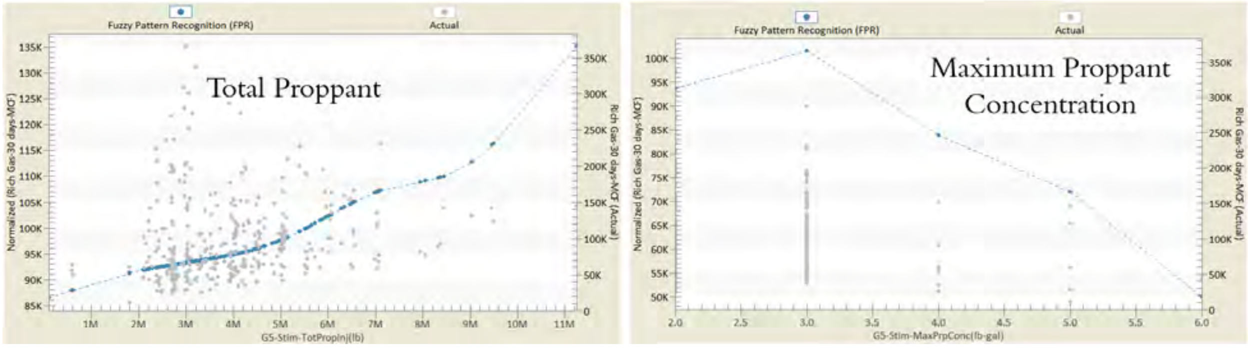


Figure 23. *Fuzzy Pattern Recognition of* ***Hydraulic Fracturing Implementation*** *for 400 Marcellus Shale wells*

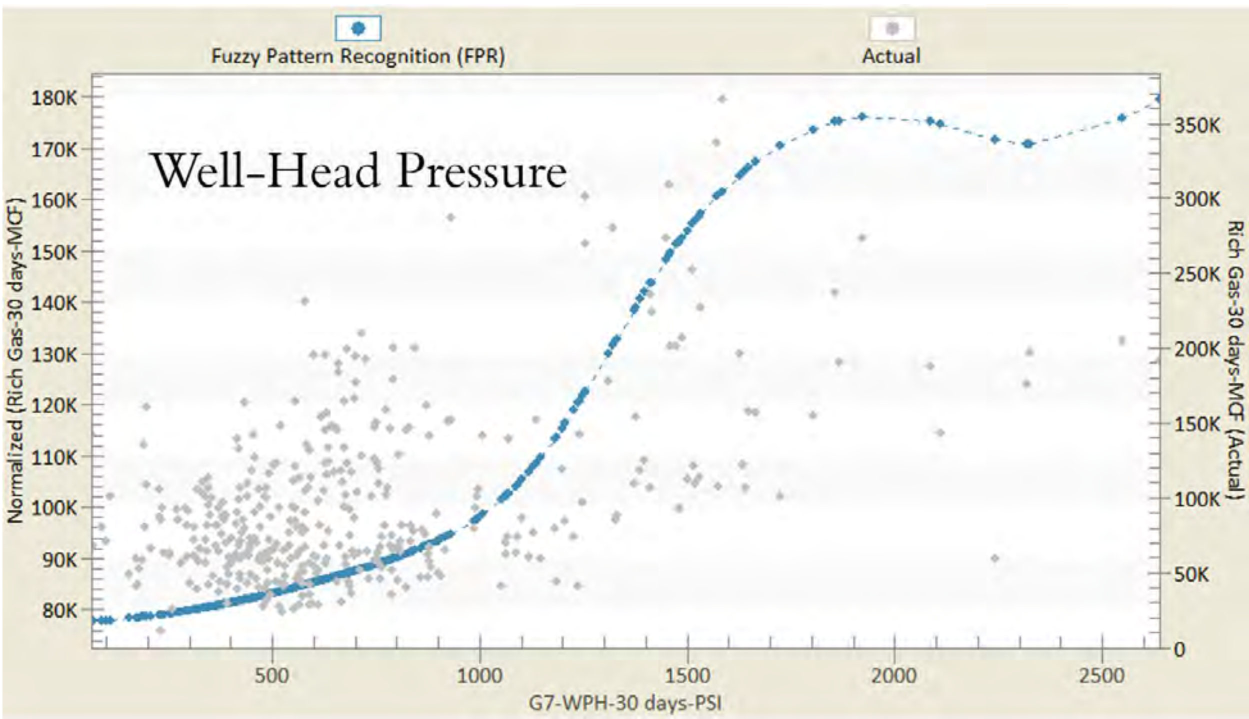


Figure 24. *Fuzzy Pattern Recognition of* ***Operational Condition*** *for 400 Marcellus Shale wells.*

Preliminary Conclusions

Identification and discovery of existing patterns from the complex (field measurements) data provided the research team with the opportunity to generate the KPI (Key Performance Indicators) for each field (asset). KPI generation contributes to the identification of the specific static and/or dynamic parameters (variables) that have the highest impact (influence) on hydrocarbon production in Marcellus and Utah shale assets. This could help future research teams to develop Predictive Models that can identify well productivity as a function of key static and dynamic parameters (variables). Once such models are developed and validated using blind data (several wells that will not be used during the Predictive Model development), then these models can be used, along with the static information from the Conasauga shale, in order to (a) estimate the most possible amount of hydrocarbon that can be produced from each well in

Conasauga shale, and (b) learn the best completion design and implementation as well as operational conditions in order to optimize hydrocarbon production from Conasauga shale.

Outcomes

Because the project was terminated prior to completion, this subtask has no outcome.

References

Mohaghegh, S.D., 2017. Shale analytics. In *Shale Analytics* (pp. 29-81). Springer, Cham.

e. Task 5 – Subsurface mapping: Seismic, potential fields, and well-tops interpretation*

By John Hickman, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 6 months of work out of the expected and budgeted 15-month research plan.)

Research staff from KGS and WVGES combined their efforts on mapping the stratigraphy of the Conasauga Group, as well as the basement fault network that dissects and compartmentalizes the Rome Trough in eastern Kentucky and West Virginia. Unfortunately, because of the shortened project term, only the well stratigraphic tops data should be considered "final", while the regional maps should be considered "preliminary" results. A Time-to-Depth conversion has not been performed on the seismic profile data, and so these "time depths" cannot be interpolated into regional elevation horizons for mapping.

The bulk of the stratigraphic interpretations were based on well data. The CSRC contains data on 292 well drilled to the Conasauga Group or deeper horizons (Figure 1), focusing on 184 near or within the Rome Trough (Figure 2). This subset includes a total of 35 wells (38 completions) with Rogersville Shale: 27 wells in KY, 6 wells in WV, and 2 wells in VA (includes the *Enervest 530555 ESUP* NETL research well). These interpretations from individual wells were then extended into regional cross sections (Figures 3a and b). Further, localized cross sections were also used for detailed analysis of the modern Rogersville UOG wells (Figure 4).

For interpreting stratigraphic surfaces between well points, the research team decided to use the basement fault maps from two previous KGS/WVGES regional projects as an initial starting point, the Trenton-Black River Research Consortium (Patchen and others, 2006), and the Utica Shale Appalachian Basin Exploration Consortium (Hickman and others, 2015). These fault maps would be refined using gravity (Figure 5), magnetic (Figure 6), and reflection seismic profile data (Figure 7). As part of the CSRC project, KGS purchased a data-use agreement for new seismic data to be used in the project (Figure 8, data provided by Evans Geophysical, Inc. of Suttons Bay, MI).

KGS then continued its subsurface stratigraphic mapping efforts using 2D reflection seismic data (Figure 7). All KGS seismic profiles in the Rome Trough region were quality checked and interpreted for both faults and stratigraphy (Figure 9), and then were leveled to account for different processing datums and remove "miss-ties" and other interpretation errors. Once this process was complete, a regional fault system map was produced across the field area (see faults displayed in Figures 5 and 6).

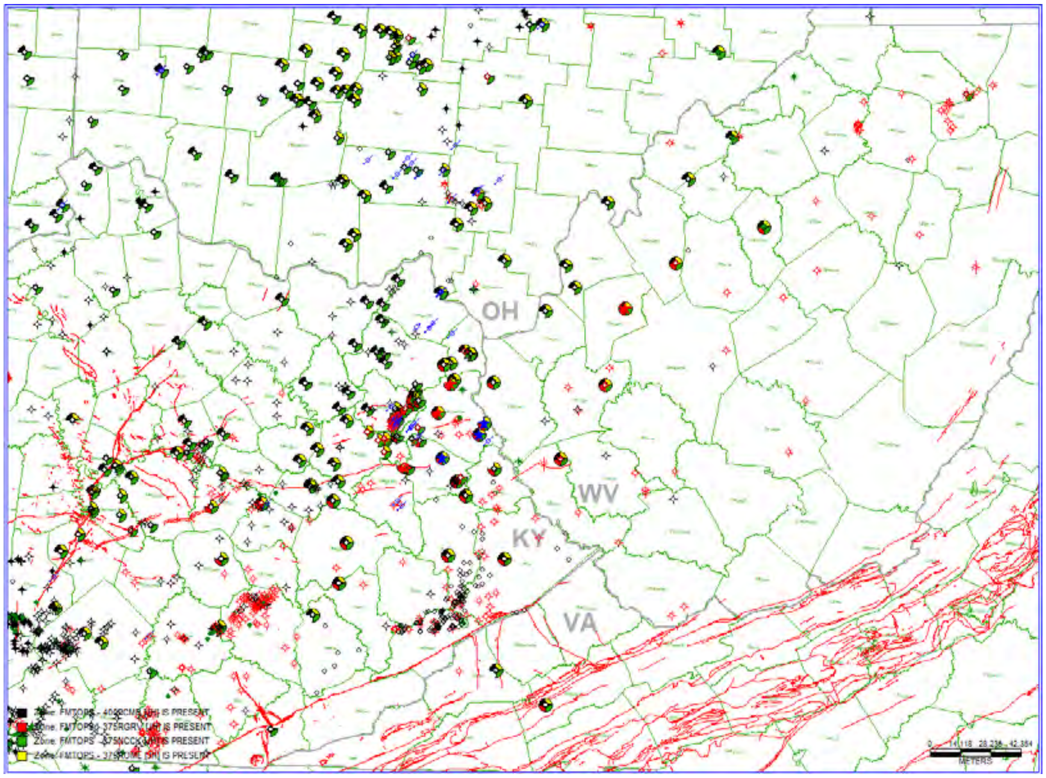


Figure 1. CSRC well dataset, with attribute map symbols indicating the presence of stratigraphic tops for the Cambrian units of Nolichucky Shale (green), Rogersville Shale (red), Rome Fm. (yellow), and the top of Precambrian basement (black). Counties are outlined in green lines, and surface faults are displayed by red lines.

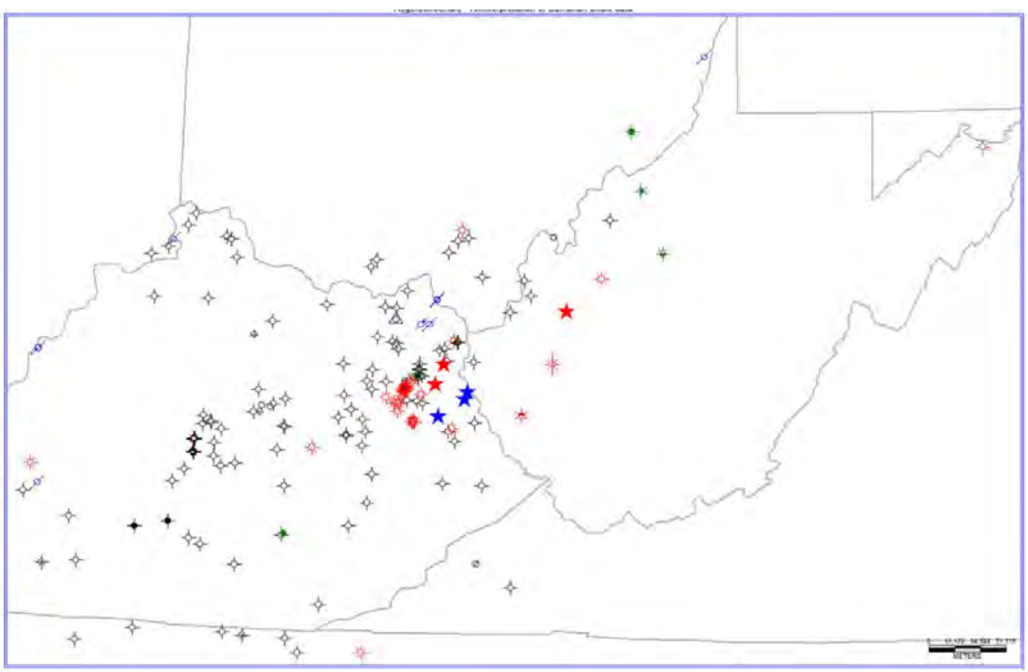


Figure 2. Core set of 184 wells drilled to Conasauga or deeper, near or within the Rome Trough used for stratigraphic analysis. The six new UOG wells targeting the Rogersville Shale (5 KY, 1 WV) are marked with stars (red are vertical wells and blue stars represent wells with horizontal lateral.

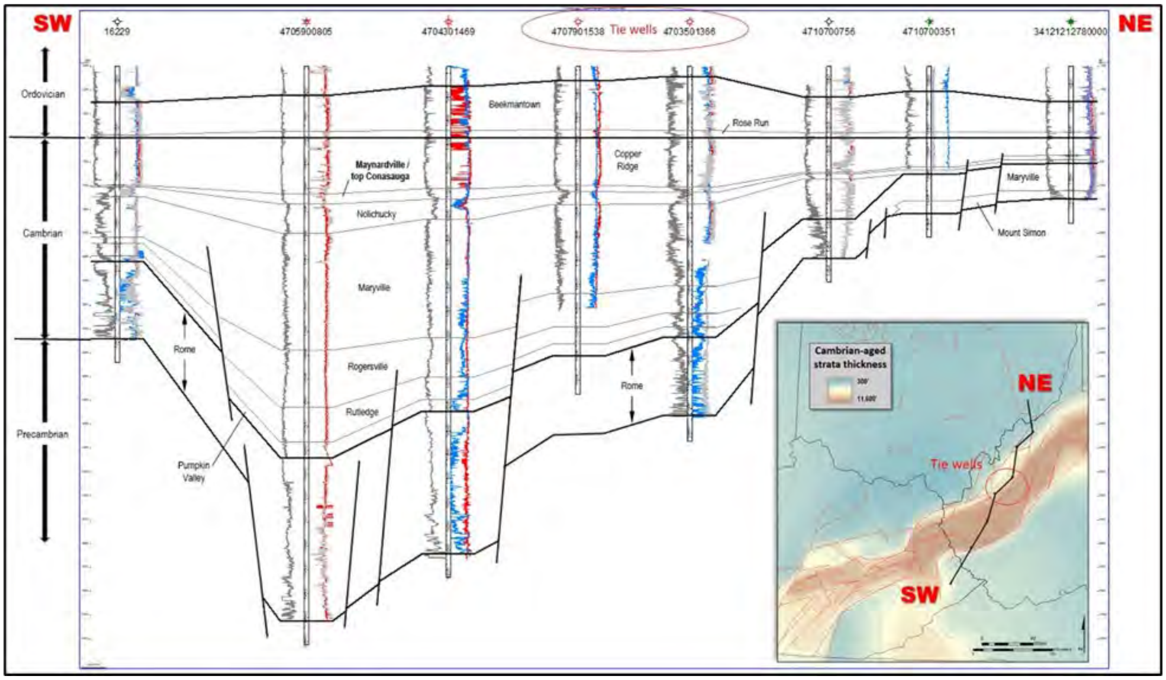


Figure 3a. A Northeast-Southwest cross section constructed using available well control in West Virginia and easternmost Kentucky.

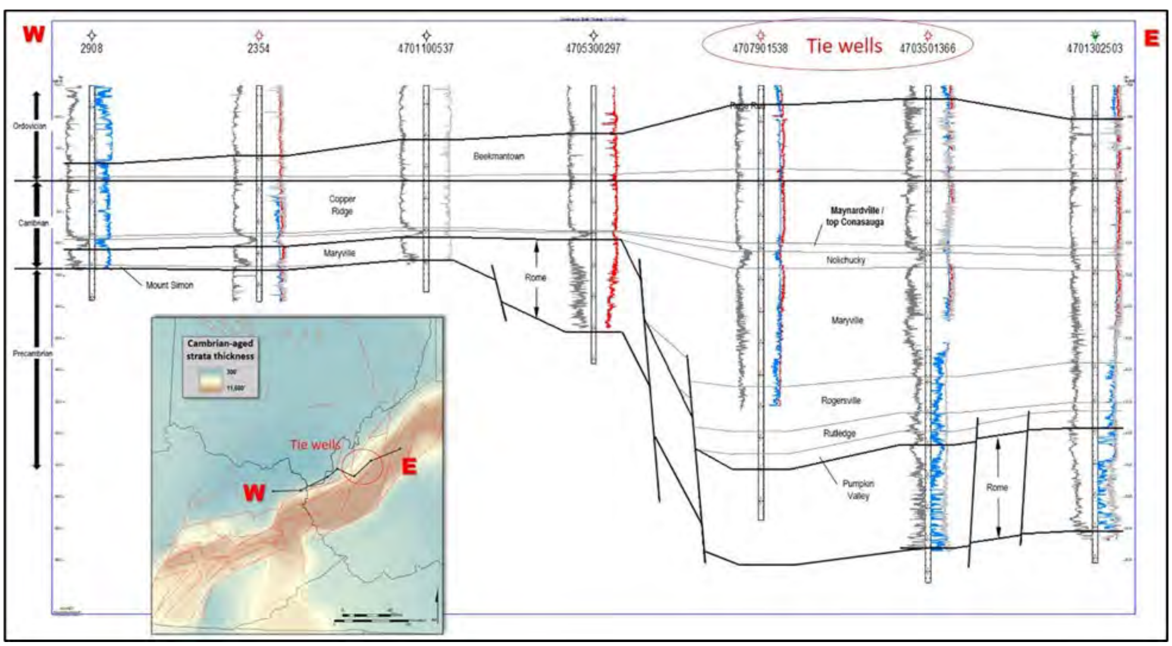


Figure 3b. A West-East cross section constructed using well control in West Virginia and easternmost Kentucky.

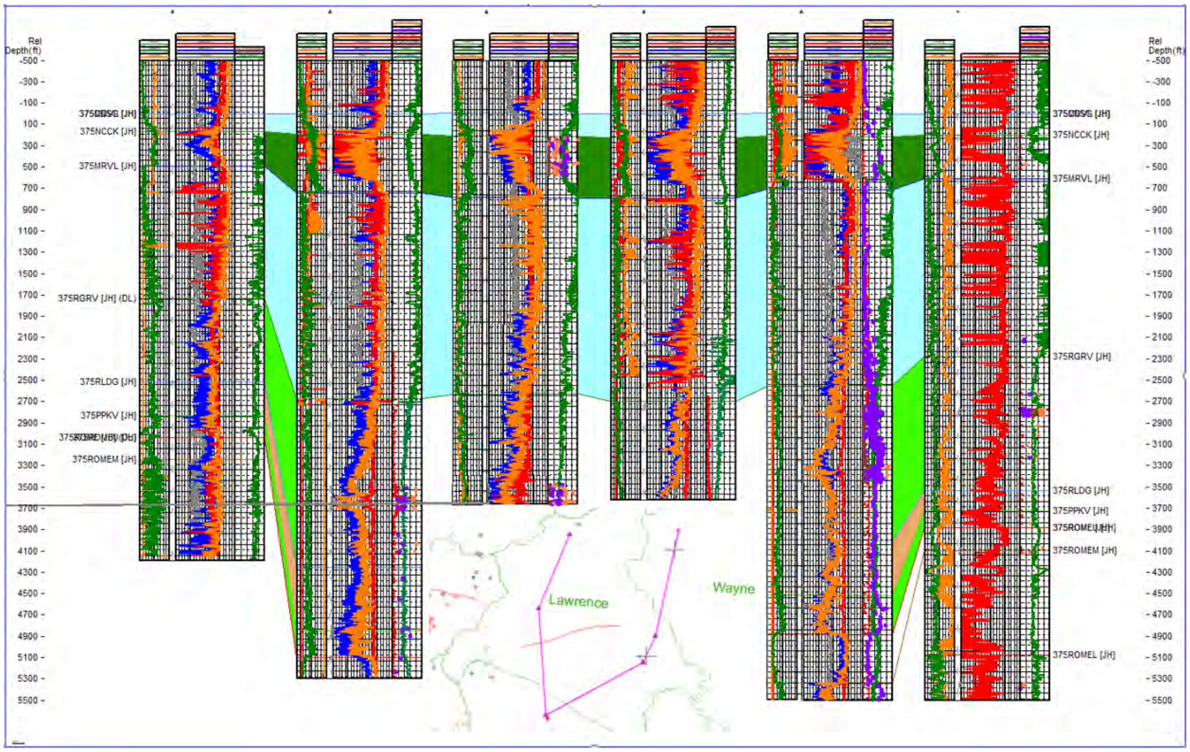


Figure 4. Well-based cross section through the Rogersville UOG wells near the KY/WV border, see inset map for locations. The Rogersville Shale is highlighted in light green, with the high TOC "sweet spot" in the lower half highlighted in orange.

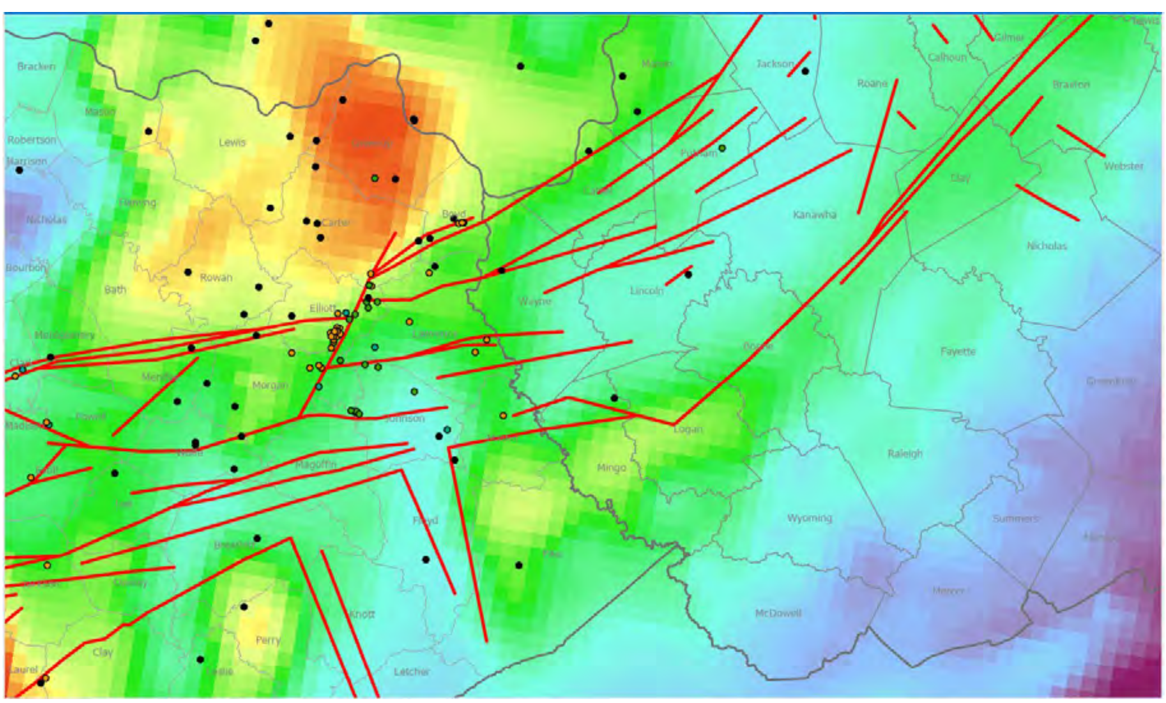


Figure 5. Bouguer Gravity survey across eastern KY and southern WV. Positive anomalies represented in "warmer" colors and negative anomalies are represented as "cooler" colors. Red lines represent basement fault trends along and in the Rome Trough.

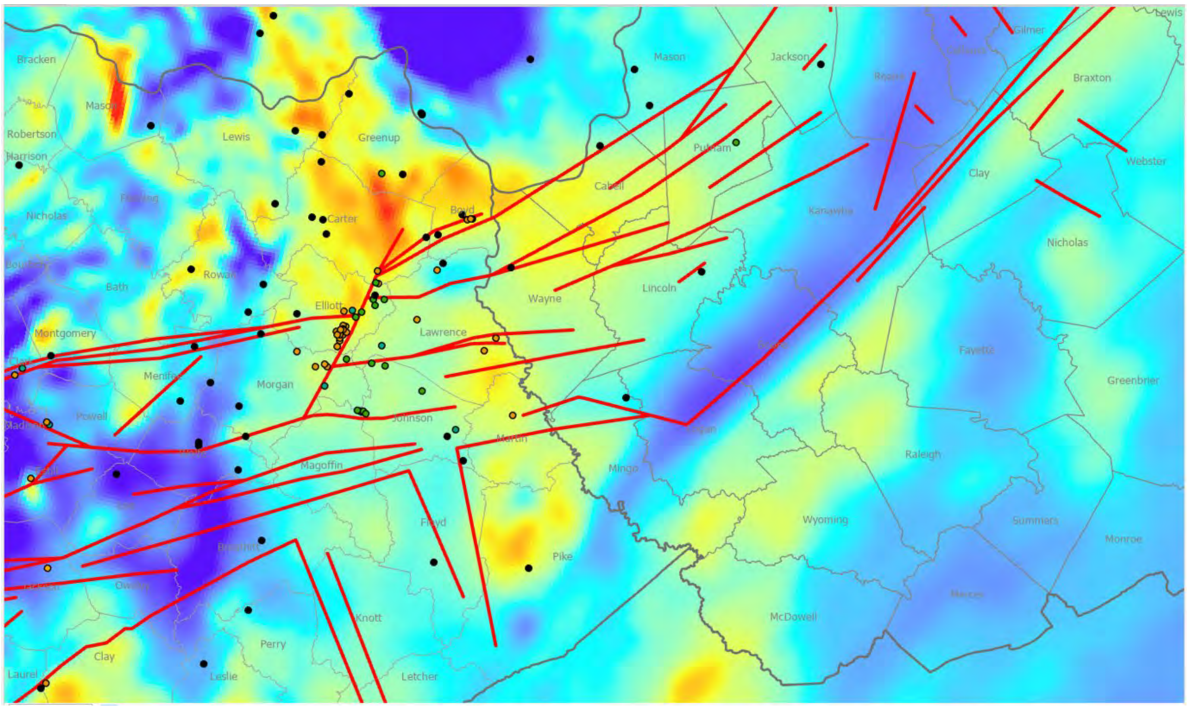


Figure 6. Reduced-to-Pole Aeromagnetic survey of eastern KY and southern WV; "hotter" colors represent positive magnetic anomalies and "colder" colors represent negative magnetic anomalies. Red lines represent basement fault trends along and in the Rome Trough.

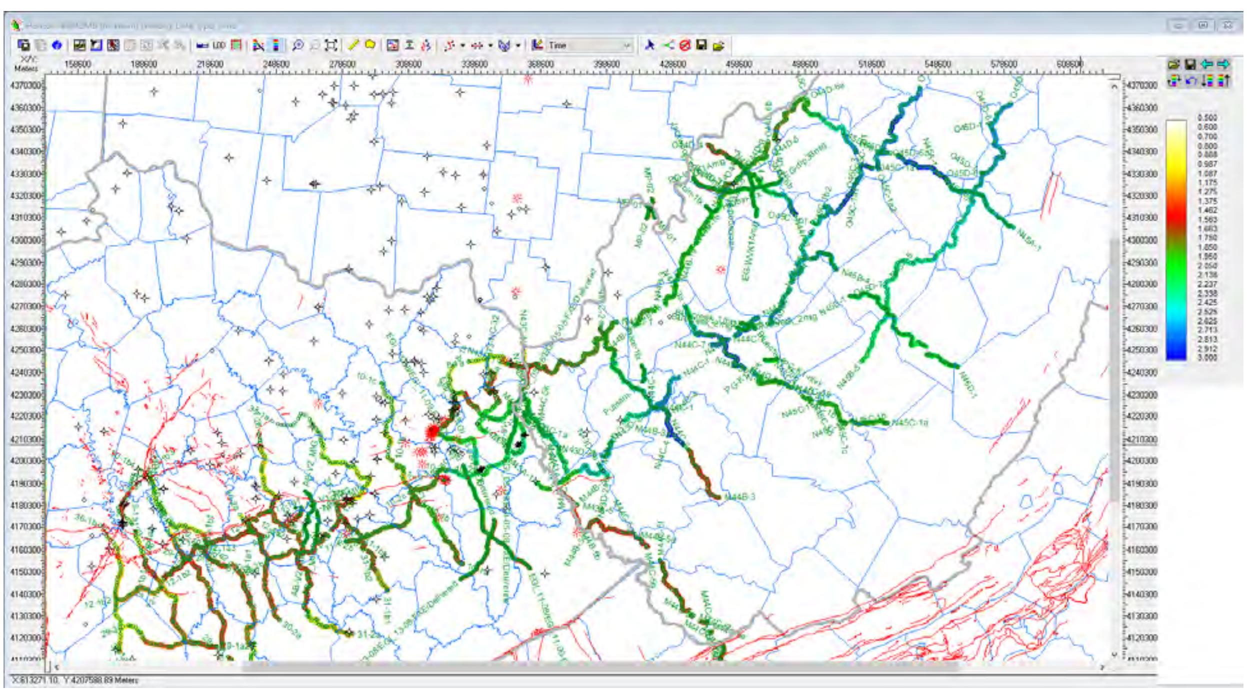


Figure 7. Map of reflection seismic data (shotpoint locations) used in the CSRC project, color coded by the two-way travel time to the top of Precambrian basement.

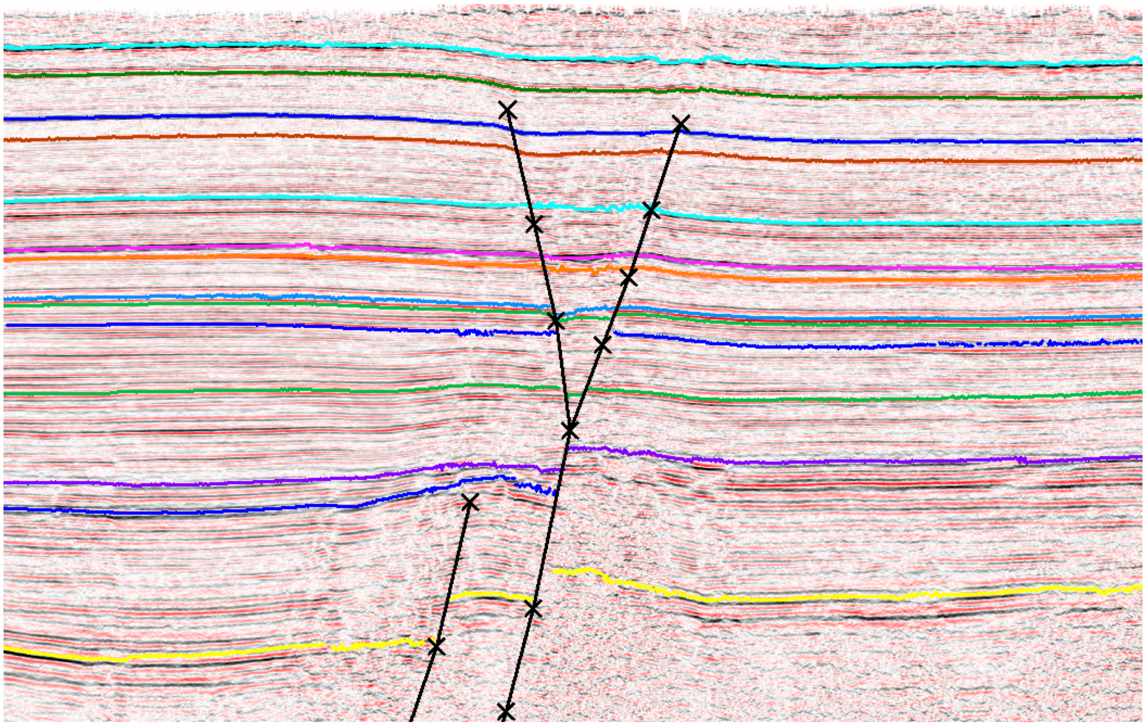


Figure 8. Interpreted seismic example from eastern Kentucky illustrating Mississippian through Precambrian strata. Reflection seismic profile acquired from Evans Geophysical, Inc. of Sutton's Bay, MI.

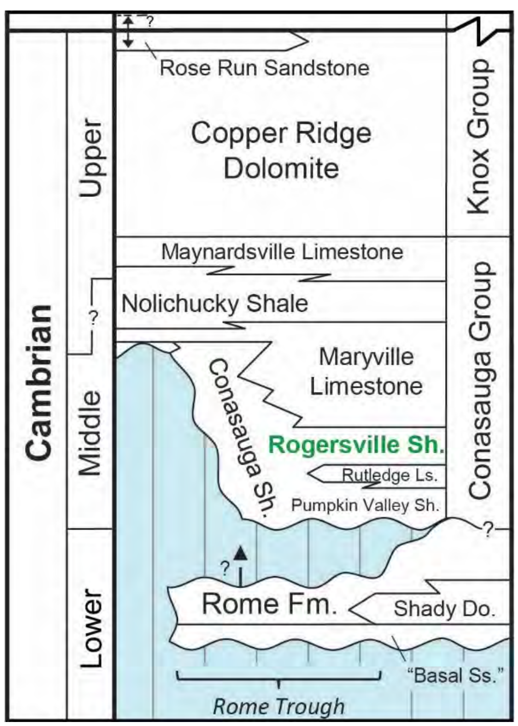


Figure 9. Cambrian stratigraphy within the Rome Trough of eastern KY and southern WV. The CSRC project focused on the three shales of the Conasauga Group: the Nolichucky, Rogersville, and Pumpkin Valley Shales. Of these, only the Rogersville Shale (highlighted in green) appears to have sufficient organic content to produce hydrocarbons.

Using the combined legacy TOC data, industry-donated TOC datasets, and CSRC samples TOC (from Task 7.1), an organically rich "sweet spot" was identified within the lower half of the Rogersville Shale. The location of this organic zone has now been interpreted through both the newer UOG shale wells and the older deep wells from the 1970's through early 2000's using the identified geophysical well log signature. The depths to this organic "sweet spot" are included in the stratigraphic tops dataset.

Unfortunately, the CSRC Project was closed before the completion of this Task could be performed, specifically the integration of the reflection seismic time horizons with the well stratigraphic depths data. However, preliminary structure and isopach thickness maps have been generated (see Figures 10 and 11, below).

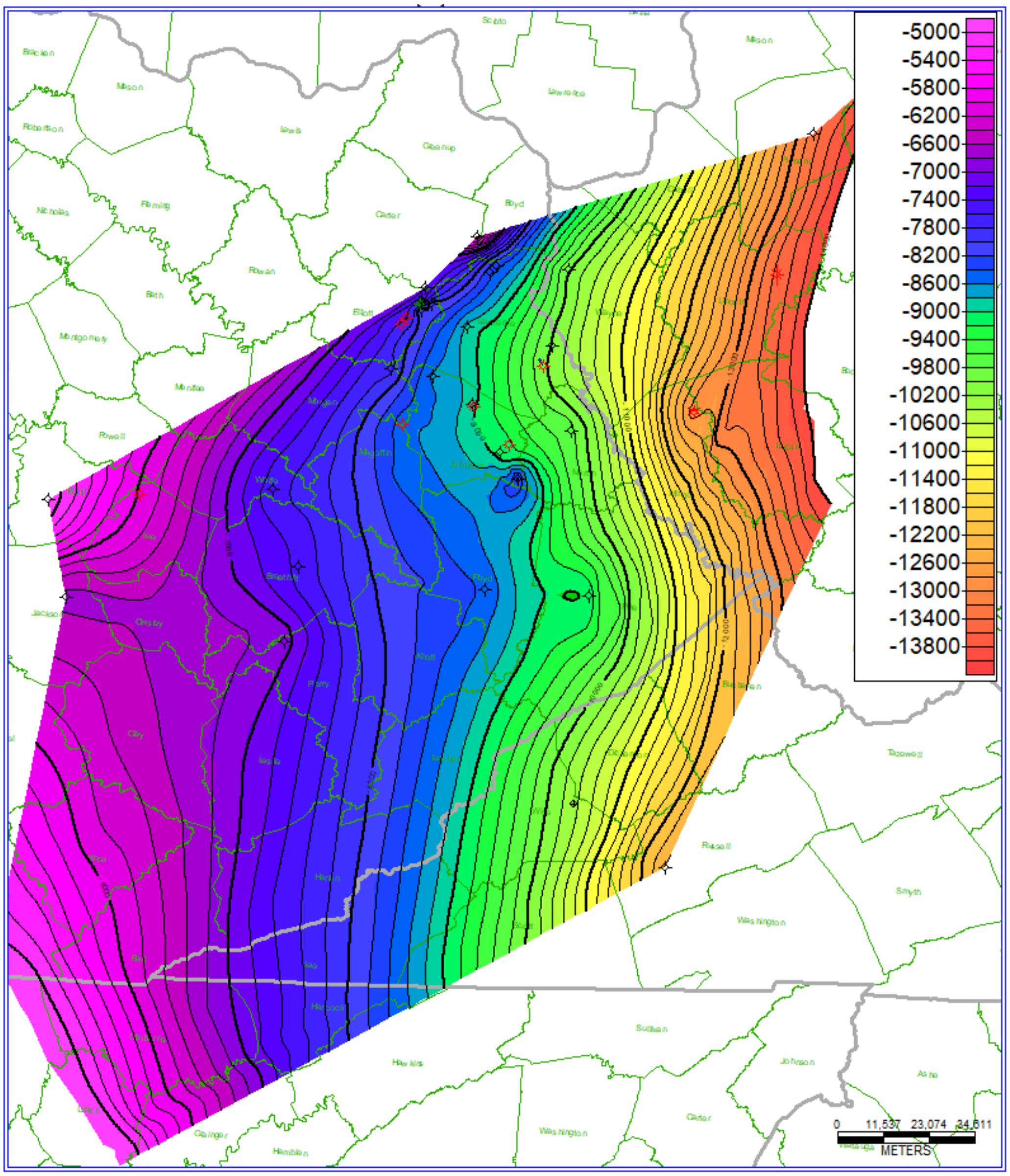


Figure 10. Preliminary Rogersville Shale structure map across eastern KY and western VA and WV, with elevations in feet relative to mean sea level.

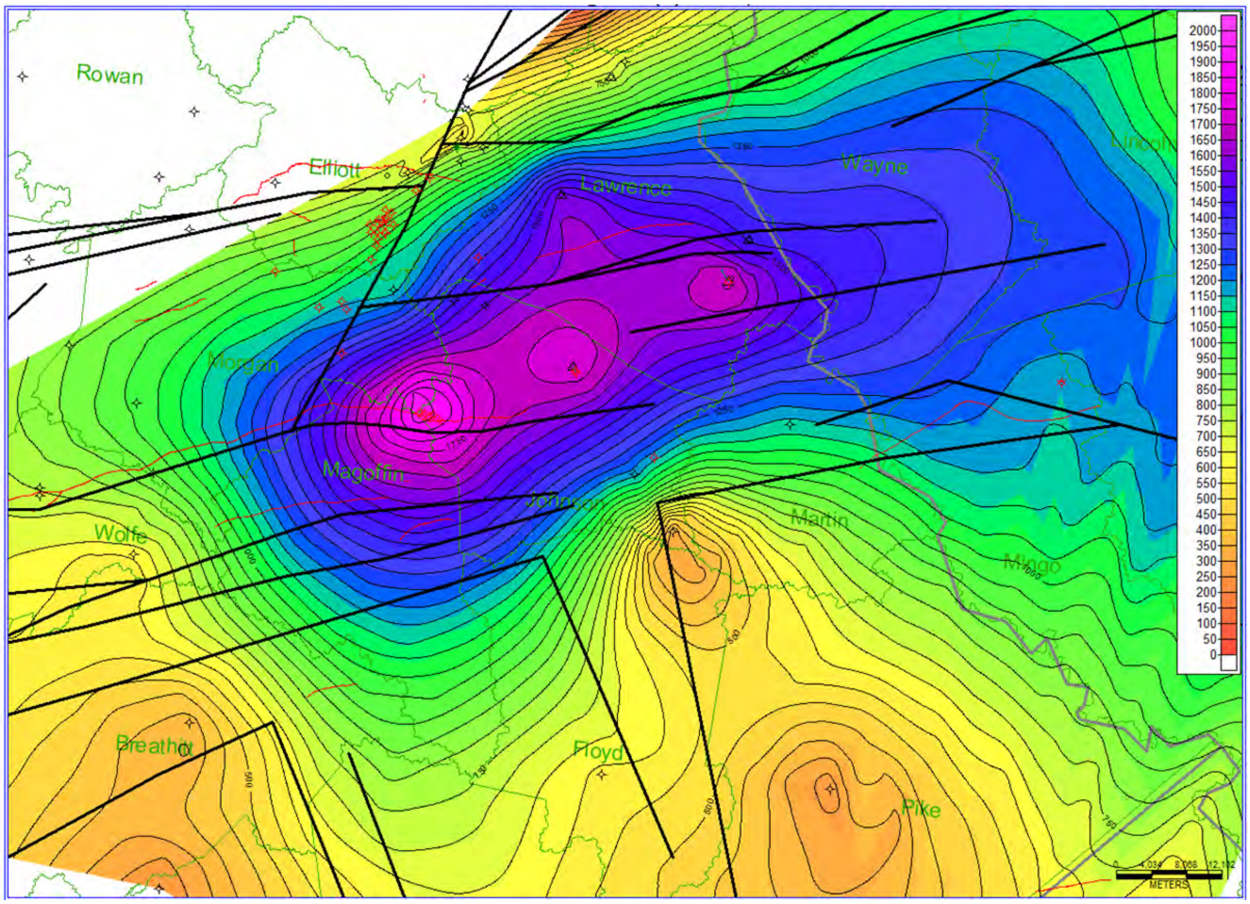


Figure 11. Preliminary Rogersville Isopach map across eastern Kentucky and southwestern WV, with thicknesses in feet. Bold black lines represent basement fault trends.

References

Hickman, J., Eble, C., Riley, R., Erenpreiss, M., Carter, K., Harper, J., Dunst, B., Smith, L., Cooney, M., Soeder, D., Metzger, G., Moore, J., Hohn, M., Pool, S., Saucer, J., Patchen, D., 2015, A Geologic Play Book for Utica Shale Appalachian Basin Exploration: Appalachian Oil & Natural Gas Consortium, Morgantown, WV, 205 p.

Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, R., Schulze, R., Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, J., Harper, J.A., Avary, K.L., Bocan, J., Hohn, M.E., and McDowell, R., 2006, A Geologic Play Book for Trenton-Black River Appalachian Basin Exploration: US-DOE Project Report Number: DE-FC26-03NT41856, 562 p., 39 pl.

f. Task 6.5 – Background seismicity characterization

By Seth Carpenter, PhD and Jonathan Schmidt

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

Introduction and Motivation

Earthquakes can result from natural causes, including the sudden release of tectonic strain through earthquake cycles and from volcanic activity. They can also be caused by manmade activities such as the injection of fluids into deep boreholes. Most seismic events triggered or induced by human activity produce very low-level shaking (Ellsworth, 2013). However, some instances of wastewater injection have reactivated faults and caused felt earthquakes, some of which were large enough to cause structural damage in local communities (Taylor et al., 2017).

Starting in approximately 2009, the rate of felt earthquakes in the central United States has increased dramatically (Fig. 1). This increased rate has a strong correlation in space and time with the increase in production of oil and gas, and resultant subsurface disposal of produced water (Weingarten et al., 2015; Langenbruch and Zoback, 2016). The principal cause of these events has been assigned to the injection of wastewater into subsurface formations (Keranen et al., 2013; Hornback et al., 2015); the largest earthquake likely induced by wastewater injection was the 2016 moment magnitude (Mw) 5.8 Pawnee, Okla., earthquake (Yeck et al., 2017). Hydraulic fracture stimulation of unconventional reservoirs, or fracking, has also induced felt earthquakes (Holland, 2013; Skoumal et al., 2015; Bao and Eaton, 2016); the largest event likely induced by fracking was the 2015 Mw 3.9 Fox Creek earthquake in Alberta, Canada. Most cases of induced, felt earthquakes were the result of fluid injection into formations that are in hydraulic communication with the crystalline basement, which can lead to the rupture of preexisting, critically stressed basement faults (Zoback et al., 2002). The National Research Council (2013) presented an in-depth introduction to the issue of induced seismicity and the mechanisms involved.

In the Rome Trough of eastern Kentucky, the Rogersville Shale, a deep formation with total organic carbon content sufficient for hydrocarbon generation, has recently been tested in exploration wells (Fig. 2; Harris, 2015). Because of its low permeability, the Rogersville Shale must be produced using unconventional methodologies—in particular, high-volume and high-pressure fracking. And, because this deep formation is in close proximity to the faulted, crystalline basement in the Rome Trough (Hickman et al., 2015; Fig. 3), there is a potential for fracking-induced earthquakes when oil and gas are produced from this shale.

In addition, produced wastewater has been injected in the eastern Kentucky Rome Tough since at least 1998 (Fig. 2; Sparks and Curl, 2014). The injection formations in the Rome Trough are relatively shallow compared to the depth of the crystalline basement (Fig. 3), and no injection-related events have been recorded by the regional seismic monitoring networks (Kentucky Geological Survey, 2014). If large-scale development of the Rogersville Shale occurs, however, the risk of inducing earthquakes from wastewater disposal could increase.

Because the possibility of inducing earthquakes in the Rome Trough may increase if the Rogersville Shale were to become a productive hydrocarbon play, acquiring background microseismicity data in the area is important. In regions of concurrent subsurface fluid injection and seismic activity, unequivocally

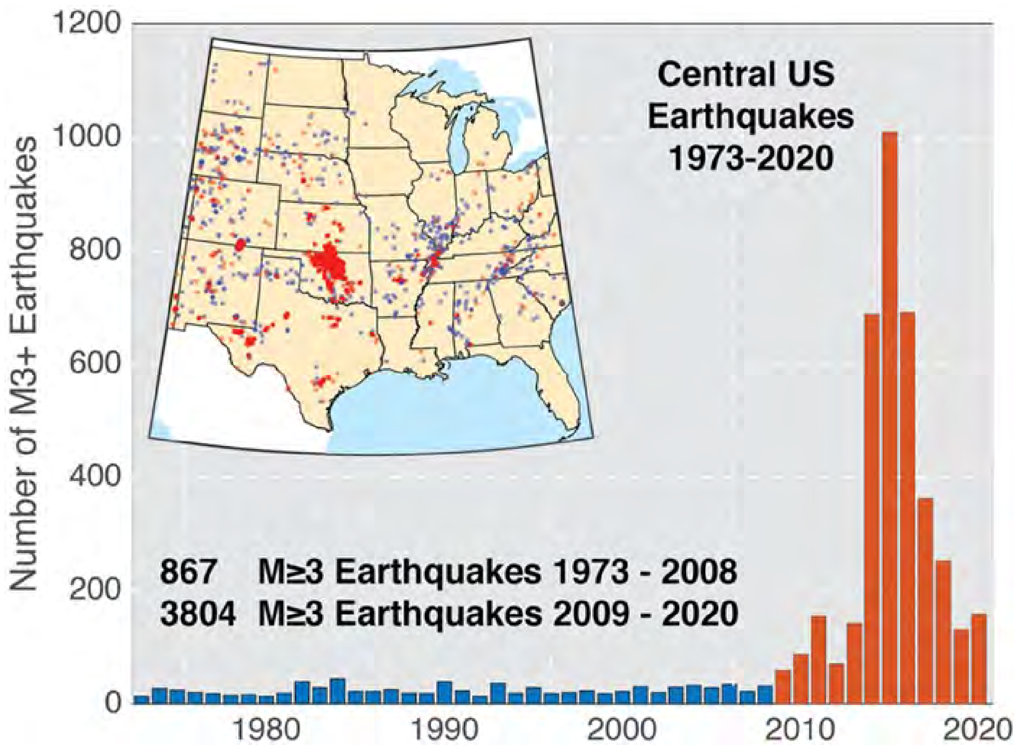


Figure 1. *Annual number of magnitude 3 and greater earthquakes in the central United States (from https://www.usgs.gov/natural-hazards/earthquake-hazards/induced-earthquakes). The annual event count for years corresponding to the shale-gas boom beginning in 2009 are in red. Inset map shows earthquake epicenters during the same period; colors correspond to those in the bar graph.*

Discriminating between natural and induced earthquakes requires the analysis of multiple data sets, including at minimum fluid-injection volume histories of active wastewater-disposal wells and an earthquake catalog. When the timing of earthquakes that occur near wastewater-injection wells and fracture stimulations is strongly correlated with the injection history, the probability of a causal relationship between the two increases. Also, cataloged seismicity-rate changes permit determining the probability that an increase in seismic activity is natural (Rubinstein et al., 2014). Natural and induced microearthquakes (earthquakes of magnitude less than 2.5) occur exponentially more frequently than larger, felt earthquakes, and are therefore a more sensitive indicator of variations in seismicity rate. Therefore, the background rates of microearthquakes are of particular importance for calculating the likelihood that earthquake activity is induced.

Following the damaging Mw 5.0 Sharpsburg earthquake in 1980 (Herrmann et al., 1982), permanent seismic stations operated by the University of Kentucky have monitored seismic activity to the north of the Trough. The active Eastern Tennessee seismic zone (Carpenter et al., 2020) abuts the Trough to the south, which is monitored by seismic stations operated by the University of Kentucky and by the University of Memphis. However, seismic monitoring stations in the region around the Rogersville Shale test wells and wastewater disposal wells are sparse. If earthquakes were to occur in the Rome Trough nearby subsurface injection wells, the existing regional stations would not permit the determination of event hypocenters (latitude, longitude, and focal depth) with sufficient accuracy and precision to associate the earthquakes with or disassociate them from the subsurface injection activities.

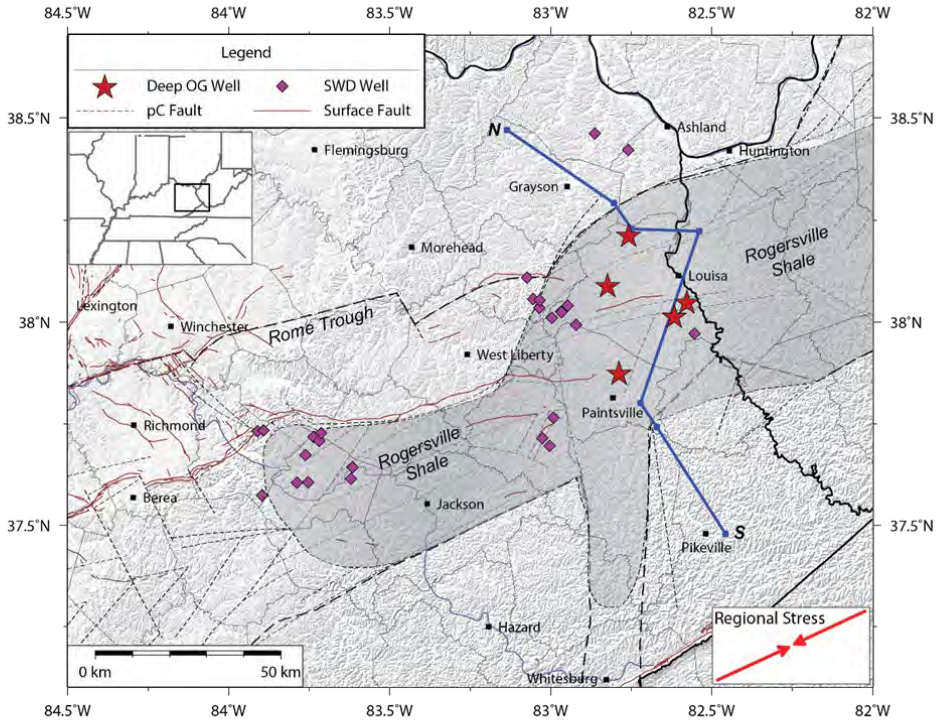


Figure 2. Surface and Precambrian (pC) faults, the Rome Trough boundary (heavy, dashed black lines), area of possible Rogersville Shale production (gray, shaded), and deep Rogersville Shale test wells (Deep OG Well) and wastewater-disposal wells (SWD well). Red arrows in the inset map show the direction of maximum horizontal regional stress. Blue line is the location of the cross section shown in Figure 3.

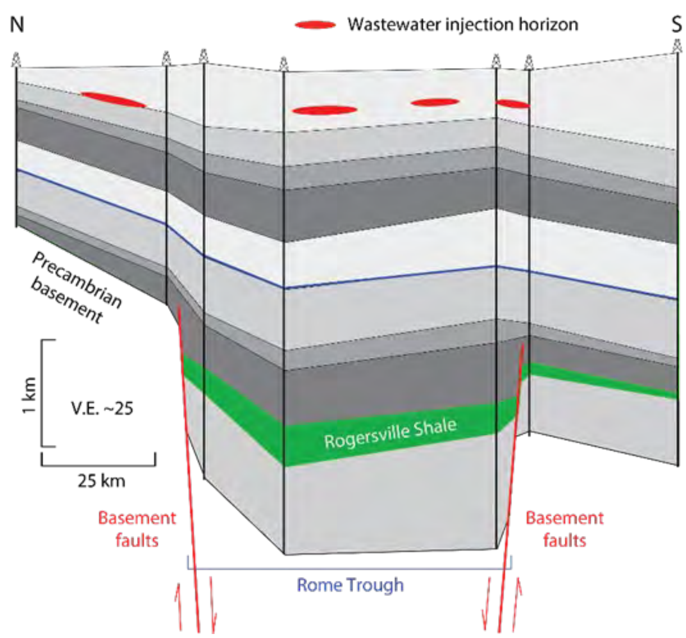


Figure 3. *Cross section based on drillers' logs, with generalized stratigraphic groups, across the Rome Trough through the study area in eastern Kentucky and southwestern West Virginia (Fig. 2). Areas marked in red refer to depths of waste-injection targets within 30 km of the section. The Rogersville Shale, the target horizon for deep fracking, is outlined in green.*

Consequently, Kentucky Geological Survey (KGS) deployed a microseismic monitoring network beginning in June 2015 to monitor the areas around clusters of existing wastewater injection wells and the areas being tested for of oil and gas production from the Rogersville Shale. KGS operated up to 14 stations simultaneously for real-time monitoring, six of which were loaned to KGS by a project partner for operation until mid-2019. The results of this study were published in 2020 (Carpenter et al., 2020). From October 1, 2019, through January 31, 2021, KGS maintained operation of eight of those stations to extend the characterization of background seismicity as part of the CSRC. This section of the report describes the monitoring network and the data analysis, and it presents the results of this 16-month investigation.

<u>Microseismicity Investigation</u>

Temporary Monitoring Network

The principal component of the project was the seismic monitoring network (Fig. 4). Instrumentation for most of the network was purchased by the Kentucky Geological Survey, with support from the University of Kentucky Department of Earth and Environmental Sciences and Nanometrics, Inc. The instruments used at each station consisted of broadband seismometers (corner periods of 120 s and high-frequency cutoffs of 100 Hz) and 24-bit data loggers which sampled the data at a rate of 200 Hz. All the stations were equipped with cellular modems for data telemetry. The metadata for the instruments operating at each network station are stored on servers at KGS.

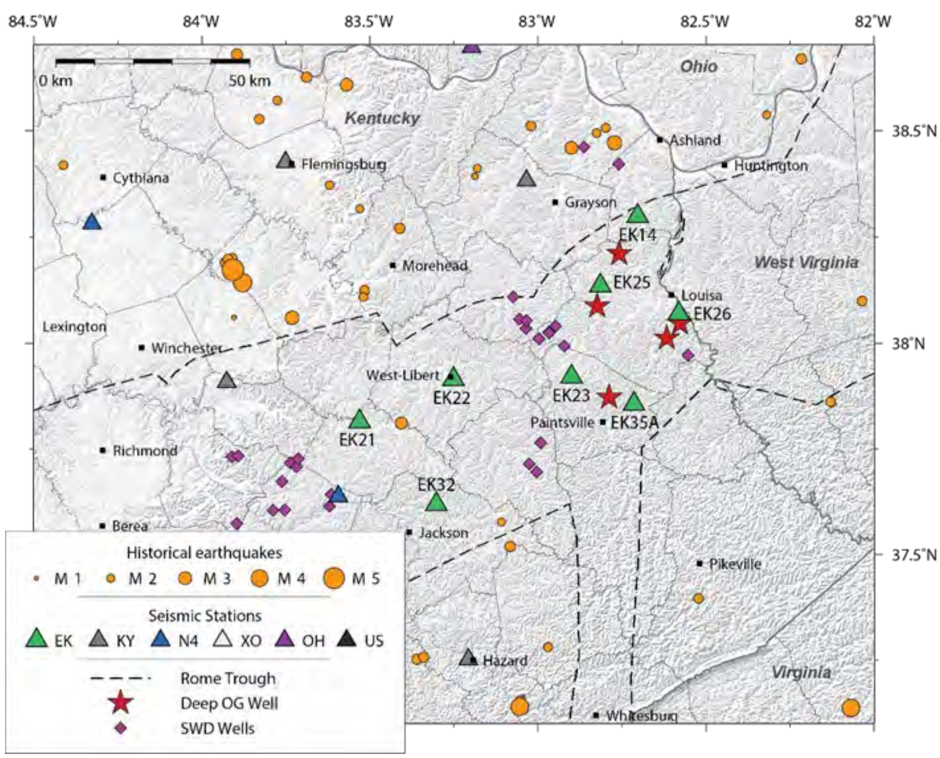


Figure 4. *Seismicity since 1980, operational UIC Class II wastewater injection wells, Rogersville Shale oil and gas test wells, CSRC microseismic monitoring stations (EK; labeled by station code), seismic stations operating during at least part of the microseismic network operation, and the boundary of the Rome Trough.*

The real-time network was designed to provide monitoring coverage in the Rome Trough in the vicinity of wastewater-injection wells and the deep exploration wells in eastern Kentucky. Station distribution was slightly denser in the eastern part of the project area, where the Rogersville Shale was considered most likely to be tested and produced. The station locations were determined to satisfy multiple criteria—including the identification of consenting landowners—that must be considered for the successful operation of telemetered, autonomous, broadband seismographs (Holcomb, 2017).

Typically, data from all telemetered stations were received at KGS for near-real-time event detection. Occasional cellular-network outages prevented the simultaneous acquisition of all stations' data, however, which temporary reduced the sensitivity of the network. One station had to be moved, EK35A, due to landowner constraints. All stations recorded data locally and the recordings, which were downloaded during routine site visits, were archived at KGS as a continuous data set. These data could be examined in a future, more complete assessment of the seismicity.

Data Acquisition and Analysis

Event Detection

Seismic events were detected using telemetered, streaming data from the microseismic monitoring network stations (Table 1) and other nearby permanent stations (Table 2). Telemetered waveforms were acquired and processed in real-time on a server at KGS using the Earthworm software package (Johnson et al., 1995). Transient signals at individual stations were detected using short-term-average to long-term-average ratios (STA/LTA) of the streaming, bandpass-filtered waveforms (Withers et al., 1998). Potential events were identified using coincidence triggering of station detections. This methodology detects seismic events—earthquakes and blasts—at local to global distance scales, depending on site noise levels and event magnitudes.

Detected events were registered into a database that was developed using the SEISAN software (Havskov and Ottemöller, 1999). Seismic events, or events detected from seismic-wave arrivals and not just recordings of correlated local noise, were categorized as either local, regional, or teleseismic based on their proximity to the monitoring network: local events were within approximately 250 km, regional events were from 250 km to 2,000 km away, and teleseismic events were at distances greater than 2,000 km. The local events were further categorized as either earthquakes or probable mine or quarry blasts based on waveform characteristics (Holcomb, 2017).

Table 1. *CSRC microseismic monitoring network station locations*

Station	***Latitude (°N)***	***Longitude (°E)***
EK14	38.2996	–82.7037
EK21	37.8160	–83.5315
EK22	37.9152	–83.2508
EK23	37.9213	–82.9004
EK25	38.1359	–82.8145
EK26	38.0704	–82.5810
EK32	37.6198	–83.3024
EK35A	37.8466	–82.6651

Table 2. *Long-term seismic monitoring stations within 100 km of the eastern Kentucky Rome Trough used to augment the CSRC real-time monitoring. Year On = Year of installation or the year when data acquisition at KGS began, whichever is later. Network codes: ET = Southern Appalachian Seismic Network, Center for Earthquake Research and Information, University of Memphis (www.fdsn.org/networks/detail/ET); KY = Kentucky Seismic and Strong-Motion Network (doi:10.7914/SN/KY); OH = Ohio Seismic Network (doi:10.7914/SN/OH); N4 = Central and Eastern United States Network (www.usarray.org/ceusn); US = United States National Seismic Network (doi:10.7914/SN/US).*

Station	***Network***	***Latitude (°N)***	***Longitude (°E)***
BHKY	KY	38.0344	–84.5032
FLKY	KY	38.4261	–83.7506
HZKY	KY	37.2511	–83.2067
PKKY	KY	38.3830	–83.0341
ROKY	KY	37.9091	–83.9257
SSFO	OH	38.6953	–83.1972
P51A	N4	39.4818	–83.0601
P53A	N4	39.4868	–81.3896
Q51A	N4	39.0260	–83.3456
Q52A	N4	38.9622	–82.2669
R49A	N4	38.2916	–85.1714
R50A	N4	38.2816	–84.3274
R53A	N4	38.3307	–81.9522
S51A	N4	37.6392	–83.5935
S54A	N4	37.7997	–81.3114
T50A	N4	37.0204	–84.8384
U54A	N4	36.5209	–81.8204
TZTN	US	36.5439	–83.5490

Data Acquisition and Analysis – Coincidence Triggering

A coincidence trigger occurs when multiple STA/LTA station detections are observed within a specified time window. For this project, Earthworm's CARLSTATRIG calculated the station detections and the CARLSUBTRIG module was used for event detection based on coincidence triggering. Prior to calculating station detections with CARLSTATRIG, broadband waveforms were filtered with a passband of 1 to 20 Hz; waveforms from short-period long-term stations were not filtered. The signal-to-noise ratio (SNR), as estimated by the STA/LTA ratio, required for a detection was approximately 3.5. For event detection, or network triggering, CARLSUBTRIG was configured to use different subsets of the monitoring network and existing seismic stations to form subnetworks.

Earthworm was configured to declare an event when detections from five stations in the project area, the largest CARLSUBTRIG subnetwork, or four stations within or near the Rome Trough were recorded within a time window of 35 s. The 35 s window is slightly longer than the travel time of a shear wave from a surface-focus seismic event traveling between the maximum distance between Rome Trough monitoring network stations (the distance between EK14 and the N4 station S51A), and thus allows all body wave triggers to arrive in the same time window for a local earthquake. To mitigate reduced detection sensitivity from temporary telemetry outages, coincidence-triggering processing was delayed by five minutes to allow late-arriving station triggers to participate in network triggering.

Machine-Learning-Based Automatic Event Identification

Coincidence triggers can result from earthquakes in or near the microseismic monitoring network as well as from larger earthquakes around the world. In addition, daily blasts at the numerous mines in and near the project area can produce detectable seismic waves that arrive within the coincidence time window (Miao et al., 2020). Furthermore, coincident random or correlated noise can trigger the Earthworm system. Because the Earthworm system was tuned to capture low-magnitude earthquakes through using both a relatively low SNR to declare a detection and a small number of detections to produce an event trigger, numerous false (noise) triggers were recorded. For example, in this project area Carpenter et al. (2020) reported that 43% of the 56,127 manually reviewed triggers from June 2015 to August 2018 — which were produced using the same Earthworm procedure as for the CSRC — were identified as noise. Of the real seismic events, 90% were from mine blasts. Thus, identifying seismic events from the numerous recordings of noise and discriminating between signals from earthquakes and from mine blasts requires significant analyst effort.

To reduce the effort required for manually classifying each CSRC event trigger, a workflow that employs Machine Learning algorithms was developed as part of this project. The workflow, which uses the GPD Predict phase picker of Ross et al. (2018; 2020) and the PhaseLink phase associator of Ross et al. (2019), eliminates most event triggers that were caused by sources of seismic energy other than local earthquakes. The GPD picker was trained on more than one million earthquake recordings and produces time series of local-earthquake P-wave and S-wave probabilities. Because blasts and earthquakes often produce considerably different waveforms, many blasts waveforms do not contain high-probability seismic phase detections. In addition, only rarely do signals from noise and distant earthquakes resemble those from local earthquakes and thus likewise often lack high-probability detections. The PhaseLink phase associator attempted to associate the P- and S-wave picks at a source location in the project area using the recording station locations, theoretical travel times (in this case calculated using the 1D velocity model used by Carpenter et al., 2020), and theoretical seismic sources distributed throughout the project area. If a sufficient number of GPD detections for a given event trigger file occurred at relative times that were consistent with a seismic source location in the project area, the trigger was considered “associated”. If not, it was rejected.

The GPD and PhaseLink algorithms were optimally configured to detect small earthquakes in the project area through tests on manually classified event triggers. Two months of triggers were used and the algorithms’ parameters were adjusted until all known earthquakes within approximately 100 km of the CSRC network were associated. The parameters that led to associating these earthquakes, while rejecting most unwanted event triggers, were requiring four or more P-wave and four or more S-wave picks with minimum probabilities of 0.555. The performance of the algorithms was largely insensitive to variations of the other parameters used to configure GPD and PhaseLink and author recommendations were used for those parameter values.

The nearly 10,000 Earthworm coincidence-based trigger files created from the beginning of the project through April 8, 2020, were manually inspected while the machine-learning-based workflow was being developed and tested. The trigger files that occurred from April 9, 2020, through the end of the project were processed through this workflow and associated events were manually inspected and classified.

Event Analysis

For all local earthquakes, first-arrival body waves were manually picked; P-wave arrivals were picked on vertical-component recordings and S-wave arrivals on transverse, horizontal components. Events were located using the Gauss-Newton algorithm HYPOCENTER (Lienert and Havskov, 1995) in SEISAN, which is discussed more fully in Holcomb (2017). The location inversion was configured to account for arrival weights based on analyst-estimated arrival-time measurement uncertainties and event-station offsets, and a regional velocity model was used to calculate the predicted first-arrival travel times and the partial-derivative matrix. Table 3 lists the weighting scheme that was used to down-weight phase arrival picks based on their arrival-time uncertainties. A distance weighting scheme was also used to further decrease arrival weights from full weight at 0 km offset to zero weight at 250 km offset. Theoretical travel times for the location inversion were calculated using the HAMBURG model (Herrmann and Ammon, 1997).

Table 3. *Arrival-time-pick uncertainties (code assigned by analyst while picking arrival times) and corresponding weights (assigned by HYPOCENTER for the arrival-time inversion) for event-location calculations.*

Code	***Uncertainty (s)***	***Weight***
0	≤ 0.075	1
1	≤ 0.15	0.75
2	≤ 0.225	0.5
3	≤ 0.3	0.25
4	> 0.3	0

Magnitudes were calculated for all located events using both an amplitude-based scale (ML) and a signal-duration based scale (Mc). Duration magnitude is determined from the coda length, or length of time from the arrival of the P-wave to when the signal amplitudes decay to background noise levels. Duration magnitudes are routinely reported by regional networks in the eastern United States and are the standard magnitude type for low-magnitude events. Therefore, the MC scale was used for events located in this study when possible.

Duration magnitudes were estimated using the relationship of Chapman et al. (2002):

$$M_c = -3.45 + 2.85\ log_{10}(D) \quad (1)$$

where D is the coda length in seconds. The median of the individual station values is reported for the event.

The local magnitude scale (ML) is determined from amplitude measurements and is analogous to the Richter magnitude scale developed for California (Richter, 1935). ML is calculated from the manually measured, maximum zero-to-peak amplitudes on all horizontal-component waveforms with discernable S-wave or Lg-wave arrivals. Prior to measuring amplitudes, the waveforms are corrected for the effects of the corresponding recording instruments, integrated to displacement, and then bandpass-filtered, following the procedure of Alsaker et al. (1991), to simulate the recordings of a Wood-Anderson seismometer, used by Richter (1935). The coefficients, which account for the S-wave and Lg-wave attenuation in the region, were calibrated by an inversion algorithm in SEISAN so that an ML 3.0 earthquake produces a displacement of 1 mm at 100 km offset, consistent with Richter's scale (Richter, 1935). Station-correction terms were also derived as part of the procedure, which accounts for any systematic biases from site effects or unmodeled instrument responses.

The local magnitude scale is less susceptible to changes in local site noise—for example, from ostensible seasonal variations and from diurnal variations from manmade sources—and therefore should provide a more consistent measurement of magnitude than the duration-magnitude scale. Furthermore, preliminary findings in Holcomb (2017) suggest that local magnitudes from the monitoring network are more consistent with the energy-based moment-magnitude scale than duration magnitudes. Thus, an ML relationship was derived for the microseismic monitoring network (Carpenter et al., 2020) and was used to calculate ML for all earthquakes located by the CSRC network. The relationship is

$$M_L = log_{10}(A) + 1.1198\, log_{10}(r) + 0.00025\, r - 1.9467 + s \quad (2)$$

where A is the displacement amplitude (zero-to-peak) in nanometers, measured on a Wood-Anderson simulated seismogram, r is the hypocentral distance in kilometers, and s is the station-specific correction term. The reported event ML is the median value of the horizontal-component magnitudes determined using equation 2.

Results and Discussion

Monitoring Network Dataset and Performance

Successful operation of the network and acquisition of its recordings have allowed an extended characterization of natural background seismicity for the project area beyond the Carpenter et al (2020) study. Figure 5 shows example seismograms from an earthquake within the project area. This example is from an ML 0.9 earthquake adjacent to the Rome Trough of eastern Kentucky. The earthquake produced high-quality recordings from CSRC monitoring network stations and several regional stations but was unreported by permanent monitoring networks.

The number of hour-long, continuous data files recorded by the CSRC network stations and the size of the finalized dataset are given in Table 4. The recordings are in miniSEED format and stored on servers at KGS. Large latencies, due to cellular network performance degradation, and malfunctioning instrumentation or extensive power outages can affect the performance of the monitoring network by temporarily decreasing its sensitivity. Thus, Table 4 also includes metrics that can be used to qualitatively assess network performance and could be used to model monitoring network performance in various network-configuration scenarios. Each station's lifespan during the 489-day project period and the percentage of that time span during which the major components of the station (seismometer and data logger) were fully operational are given in Table 4. Table 4 also lists estimates of the real-time data completeness for each monitoring station, which is given in terms of the percentage of the operational lifespan that a station's streaming recordings were available for real-time Earthworm processing.

Table 4 shows that all stations except one operated completely successfully (i.e. there were no instrumentation problems) throughout the duration of the project period and that the data for these stations were available for real-time analysis nearly 99 percent of the time on average. The station EK35A, which had to be moved at the beginning of the project, required repair but still operated for 70 percent of the project period. This station also experienced the greatest latency, but the streaming data were still available for real-time analysis 88 percent of the station's lifespan. Because the earthquake rate is very low in the project area (Carpenter et al., 2020) and the data from all stations were available for most of the project period, it is unlikely many small-magnitude earthquakes were missed due to telemetry or station problems.

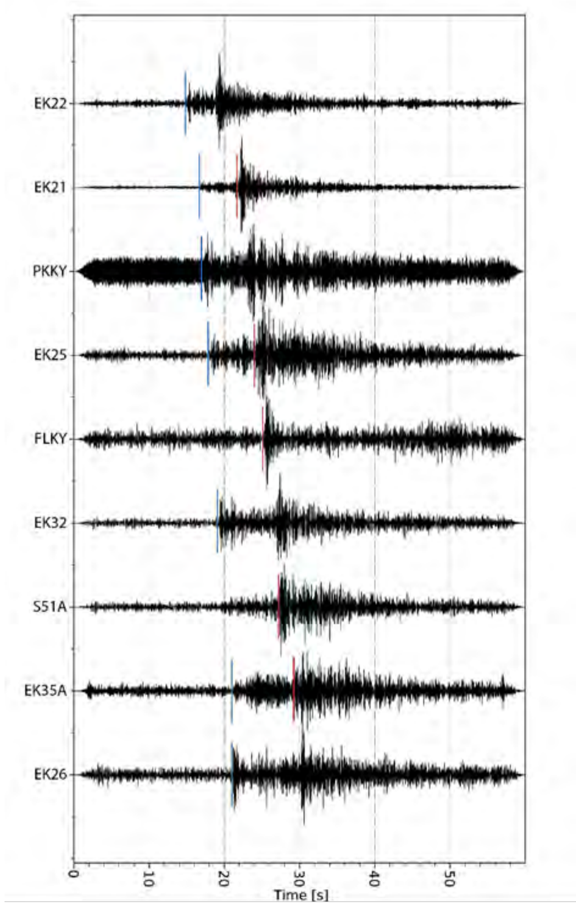


Figure 5. *Seismograms from an ML 0.9 earthquake just north of the eastern Kentucky Rome Trough recorded by CSRC and other permanent seismic stations at distances from 23 km to 67 km from the hypocenter. Blue vertical lines mark P-wave arrivals and red vertical lines mark S-wave arrivals on selected seismograms.*

Table 4. *CSRC microseismic monitoring project data set, station operational periods, and telemetry latencies. N = Number of hour-long miniSEED data files recorded. Size = Total size of the data volume for this station. Lifespan = the number of days the station operated through the CSRC project period of 489 days. Operational percentage = the percentage of the lifespan during which a station's data logger and seismometer functioned properly. Latency = the estimated percentage of a station's lifespan that data streams latent for more than five minutes, and thus unavailable for real-time event detection. Real-time Availability = 100 minus the Latency.*

Station	***N***	***Size (GB)***	***Lifespan (days)***	***Operational Percentage***	***Latency (%)***	***Real-time Availability (%)***
EK14	35,208	31.8	489	100.0	0.12	99.88
EK21	35,208	56.2	489	100.0	0.70	99.30
EK22	35,169	56.2	489	100.0	0.94	99.06
EK23	35,208	32.0	489	100.0	1.34	98.66
EK25	35,208	31.8	489	100.0	1.52	98.48
EK26	35,208	31.8	489	100.0	1.46	98.54
EK32	35,208	56.2	489	100.0	0.76	99.24
EK35A	23,859	21.6	340	96.7	12.05	87.95

Trigger Filtering Using Machine Learning

The monitoring network and contributing regional stations detected 33,753 events by coincidence triggering from October 1, 2019, through January 31, 2021. Triggers from the first six months (October 1, 2019, through April 8, 2020) were manually classified, and identified seismic events were registered into the SEISAN database. The automated machine-learning-based event associator was used from April 9, 2020, through the end of the project to reduce the number of triggers that required manual inspection. As Figure 6a shows, all but 318 of the 23,885 triggers recorded during that time were rejected. Thus, only 1.3 percent of the triggers passed, reducing the effort of an analyst to manually classify the events by approximately 98.7 percent.

Figure 6a also shows that 245 triggers contained detections from real seismic events that were associated. Of these 193 (78.7 percent) were classified as mine blasts, four (1.6 percent) were classified as regional earthquakes (> 250 km from the CSRC network), 25 (10.2 percent) were classified as teleseismic or global earthquakes (> 2,000 km from the CSRC network), and 23 (9.4 percent) events were local earthquakes. Local earthquakes occurred at a rate of 2.4/month on average and the monthly counts shown in Figure 6b do not reveal any obvious reduction of earthquake rate when the machine-learning-based workflow was used. Lacking such a reduction suggests that there was no systematic loss of local earthquake triggers by this workflow.

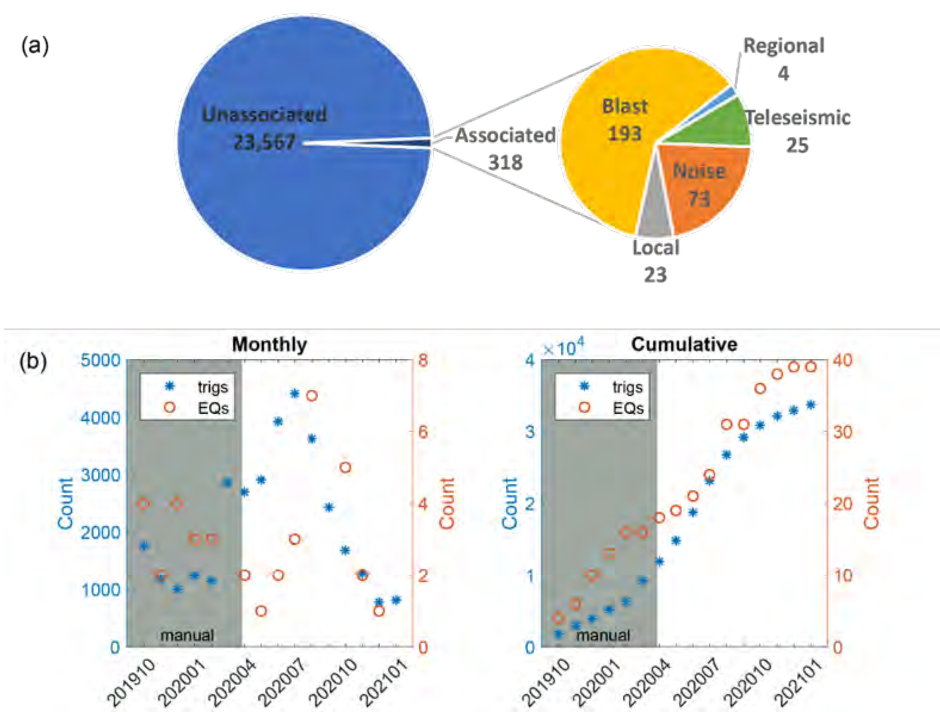


Figure 6. *(a) Result of applying the automated machine-learning-based event associator to the dataset of triggers generated by the Earthworm real-time processing. All but 318 of the 23,885 triggers were removed from the dataset (Left). Those with associated arrivals were manually classified as noise or seismic event (Right; categories shown). (b) Counts of monthly (left) and cumulative (right) Earthworm triggers (trigs) and cataloged earthquakes (Eqs) during the CSRC. Shaded regions in each plot delineate the time period when and the machine-learning-based associator was not used and all triggers were manually inspected.*

Seismicity

In total, 39 triggered events were classified as local earthquakes (Table 5; Fig. 7). SEISAN was used to determine the hypocentral location and to calculate the local magnitude for each of these earthquakes, except those associated with the 2020 Sparta, NC earthquake sequence. Although the four events associated with the Sparta, NC, sequence were well detected by the CSRC, the locations determined by the U.S. Geological Survey, which were better constrained through their use of additional seismic stations to the east of the source zone, were adopted for the CSRC catalog. Fewer earthquakes (eight) were reported in the CERI earthquake catalog in the same region (www.memphis.edu/ceri/seismic; which is the exclusive source for earthquake parameters used by the U.S. Geological Survey in this region) during the CSRC seismic monitoring project period. The earthquake locations in the CERI catalog are generally similar to the corresponding event locations determined by the CSRC. The earthquake focal depths, with a median depth of 14.9 km, were consistent with previously observed seismicity in the project area (Carpenter et al., 2014; 2020). And the spatial distribution of the seismicity observed by the monitoring network is consistent with the long-term seismicity catalog for the region (compare Figs. 4 and 7).

Within 100 km of the CSRC network stations (boxed region in Fig. 7) 15 earthquakes were detected. Notably, only three of those earthquakes occurred in the crust beneath the Rome Trough—where the network was the most sensitive—none of which were near the region of potential hydrocarbon production from the Rogersville Shale. Also, no earthquakes occurred closer than 10 km to any wastewater disposal well. Thus, it is unlikely that any earthquakes were associated with subsurface wastewater disposal. The contrast in seismic activity within and outside of the Rome Trough suggests a difference in the earthquake potential of the Trough compared to the surrounding regions; additional research is needed to constrain the cause of the difference. Carpenter et al. (2020) raised the possibility that most faults large enough to produce detectable earthquakes within the Rome Trough in eastern Kentucky and western West Virginia trend subparallel to the orientation of maximum compressive stress at seismogenic depths, and thus these faults would not be favorably aligned for failure in the current stress regime.

A Gutenberg-Richter plot of the seismicity in Table 5 is shown in Figure 8. The cumulative number of events per year above a given magnitude versus magnitude are plotted on Gutenberg-Richter curves, the linear parts of which are useful to determine recurrence rates. Globally, where seismicity is caused by tectonic stress release through brittle failure on existing faults, the magnitude of the slope of the linear part, the b-value, is approximately 1.0 (Stein and Wysession, 2009). Assuming seismicity is a self-similar, or fractal, process, the minimum magnitude of the linear part of the Gutenberg-Richter curve is considered to represent the low-magnitude limit of a catalog's completeness, or the magnitude above which all earthquakes in the region have been detected. The b-value determined for the CSRC catalog is 1.0, consistent with global seismicity observations. This suggests that tectonic strain is released through earthquake activity in the vicinity of the project area in a self-scaling process, as is the typical case globally. The curve shown in Figure 8 was also used to estimate the magnitude of completeness of ML 1.8 using the maximum-curvature method (Wiemer and Wyss, 2000).

Regions of variable seismic activity are included in the project area—the active Eastern Tennessee Seismic Zone to the south of the Rome Trough of eastern Kentucky (Carpenter et al., 2014), the active region to the north of the Trough, and the relatively inactive Rome Trough itself—and thus events from regions with different seismicity rates (ordinates of the Gutenberg-Richter plots) were included in the monitoring-project event catalog. There are too few events in the project area to analyze these regions with separate Gutenberg-Richter plots, however, and therefore the curves reveal an area-weighted average of the b-values, seismicity rates, and catalog completeness estimations across these regions. The other important factors that affect the catalog completeness estimate include differences in network sensitivity due to variations in the site noise levels between day- and nighttime hours and occasional station and telemetry outages.

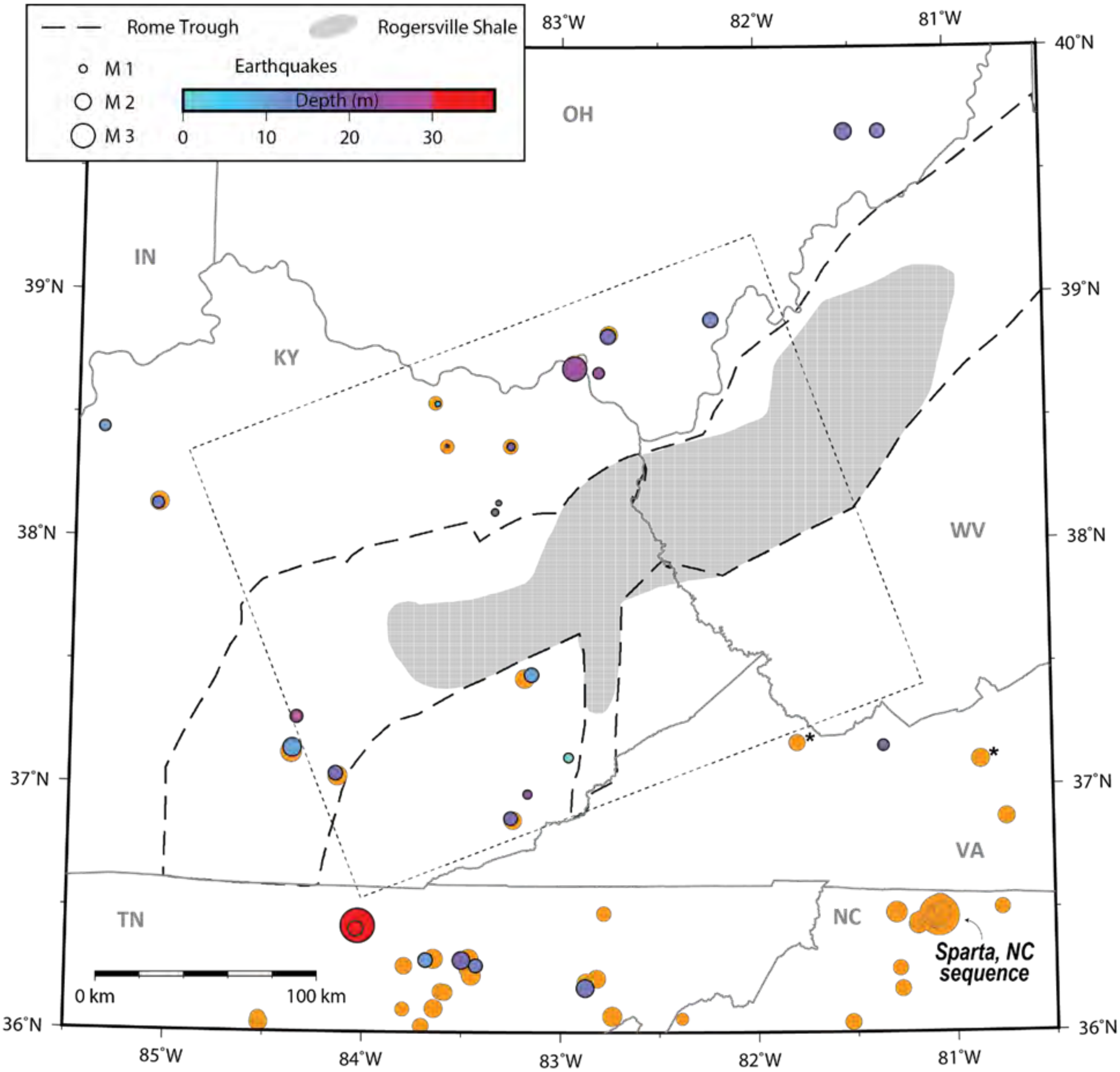


Figure 7. *Seismicity detected by the CSRC microseismic monitoring network (colored by focal depth) and in the CERI earthquake catalog (see text for description; orange) for the same period. The four earthquakes detected by the CSRC network and associated with the 2020 magnitude 5.1 Sparta, NC, earthquake sequence are not shown because the CERI locations for these events were adopted. Two seismic events located in Virginia that were published in the CERI catalog as earthquakes were determined by KGS to be potentially associated with manmade activities such as mining and were not included in the CSRC earthquake catalog (Table 5). These events are labeled with an asterisk. The dotted box encloses earthquakes within 100 km of a CSRC network station.*

Table 5. *Local earthquake source and location-quality parameters. Depth is with respect to sea level. ML is calculated using equation 2; Mc is from equation 1. RMS = root-mean-square of the arrival-time residuals for the reported location. Npha = number of phases used to determine the hypocenter. Gap = The largest azimuthal separation between stations used to determine the hypocenter. Dmin = distance to the closest station used to determine the hypocenter. Elon = standard error in longitude. Elat = standard error in latitude. EZ = standard error in depth. Records that lack magnitudes and location-quality parameters are for earthquakes associated with the 2020 magnitude 5.1 Sparta, North Carolina, event sequence, which were detected by CSRC stations, but not located as part of this project. The locations shown are from the CERI earthquake catalog (https://www.memphis.edu/ceri/seismic/). Null values are designated by "-".*

Date	Time	Latitude (ºN)	Longitude (ºE)	Depth (km)	M_L	M_C	RMS (s)	N_{pha}	Gap (º)	D_{min} (km)	E_{lon} (km)	E_{lat} (km)	EZ (km)
2019/10/07	09:23:03.7	38.1334	-85.0794	15.3	1.5	2.3	0.14	13	85	19.3	2.1	1.4	3.6
2019/10/12	17:39:52.5	37.1514	-84.3683	10.1	2.3	3.1	0.36	21	98	44.2	3.0	3.0	34.6
2019/10/21	00:34:53.0	39.6548	-81.5232	15.0	2.1	2.2	0.19	7	262	21.9	32.7	81.8	93.5
2019/10/24	07:32:15.0	38.5502	-83.6437	8.2	0.7	1.2	0.28	11	142	16.6	2.4	2.7	7.0
2019/11/03	03:17:48.9	39.6566	-81.3463	12.9	1.8	2.0	0.33	17	89	19.2	1.5	2.4	7.5
2019/11/11	20:13:58.9	37.2763	-84.3367	18.4	1.6	2.3	0.20	15	89	52.8	2.6	2.6	5.1
2019/12/10	04:10:08.8	37.4924	-80.3440	14.3	1.9	-	0.30	12	112	89.9	3.8	3.6	11.0
2019/12/10	06:43:10.8	37.4591	-80.3622	14.9	2.2	2.1	0.18	8	212	28.0	11.3	10.6	23.7
2019/12/10	10:02:57.0	37.4891	-80.3232	11.1	1.8	-	0.16	7	169	89.9	5.2	4.7	54.9
2019/12/31	02:21:02.3	38.3793	-83.2624	19.9	1.0	1.4	0.09	14	172	19.9	2.5	1.5	7.8
2020/01/05	19:13:22.6	37.4530	-83.1508	10.0	1.8	3.1	0.29	16	108	22.8	1.6	4.5	8.1
2020/01/19	10:19:24.0	36.4282	-84.0309	32.6	2.6	-	0.14	17	158	13.1	2.9	1.3	2.8
2020/01/20	19:12:11.3	36.4304	-84.0258	31.4	4.3	-	0.21	28	157	13.6	2.4	1.4	2.3
2020/02/09	12:28:24.8	38.4399	-85.3653	10.0	1.4	1.7	0.18	8	327	23.6	17.9	14.1	27.3
2020/02/12	03:14:20.9	36.9679	-83.1698	22.5	1.1	1.4	0.12	9	203	31.6	4.1	14.0	7.5
2020/02/12	17:33:03.9	36.4181	-84.0344	31.7	1.9	2.2	0.28	14	164	12.7	2.6	2.1	2.9
2020/04/25	10:33:48.8	38.7016	-82.9360	28.0	3.0	3.5	0.14	24	101	36.4	0.8	1.2	3.3
2020/04/29	09:13:49.0	36.2917	-83.5010	17.2	2.2	1.7	0.29	17	225	4.5	4.4	3.6	2.7
2020/05/22	05:58:41.7	37.0495	-84.1459	17.4	1.8	2.1	0.11	16	86	61.7	1.0	1.4	3.5
2020/06/04	21:08:14.8	36.2923	-83.6808	11.1	1.8	2.0	0.15	10	230	18.8	2.0	2.3	4.3
2020/06/21	12:30:28.8	36.0697	-82.7300	6.8	1.8	2.5	0.16	17	104	5.4	1.2	2.3	1.3
2020/07/29	00:36:35.8	38.2036	-79.9031	12.0	2.7	-	0.12	12	201	119.0	7.3	13.7	26.5
2020/07/29	18:56:11.3	38.1501	-83.3245	15.0	0.7	-	0.12	13	103	26.9	1.9	1.8	6.2
2020/07/30	05:57:13.7	38.2143	-79.9052	11.5	2.6	2.2	0.15	9	201	120.0	3.9	6.0	15.5
2020/08/03	02:03:41.0	35.9136	-83.6146	17.7	2.3	2.6	0.08	11	251	47.5	6.3	2.9	4.4
2020/08/09	05:56:51.2	36.478	-81.089	4.1	-	-	-	-	-	-	-	-	-
2020/08/09	12:07:37.7	36.476	-81.094	7.6	-	-	-	-	-	-	-	-	-
2020/08/11	20:45:27.0	36.472	-81.109	3.1	-	-	-	-	-	-	-	-	-
2020/08/21	13:53:45.8	38.1132	-83.3423	22.5	0.9		0.14	13	108	23.4	1.9	2.1	3.6
2020/08/23	22:17:43.1	38.6784	-82.8090	25.0	1.4	2.0	0.11	15	164	38.2	2.3	5.2	6.4

2020/08/28	03:53:47.6	36.2706	-83.4270	14.4	1.7	-	0.11	10	280	7.6	8.8	3.9	5.4
2020/10/01	19:53:14.3	36.490	-81.303	4.2	-	-	-	-	-	-	-	-	-
2020/10/08	07:50:50.6	38.8259	-82.7615	16.0	1.9	2.4	0.14	19	124	55.3	1.7	2.5	3.7
2020/10/21	15:38:33.7	36.8690	-83.2548	17.0	1.7	2.0	0.19	17	96	42.6	1.2	3.2	4.2
2020/10/25	17:18:53.0	35.3913	-84.0557	10.0	2.3	2.4	0.13	10	303	113.0	302.5	52.1	115.2
2020/10/31	15:53:45.2	36.1805	-82.8761	15.0	2.2	2.3	0.13	9	219	56.3	26.1	6.2	36.7
2020/11/12	10:13:52.5	37.1164	-82.9621	0.0	1.2	1.9	0.14	9	202	26.4	2.6	6.4	6.8
2020/11/27	10:06:18.1	38.3800	-83.5922	23.0	0.4	1.1	0.11	13	100	14.7	1.5	2.6	4.2
2020/12/28	22:26:58.5	38.8932	-82.2285	11.9	1.9	2.2	0.16	12	151	8.3	2.5	4.6	3.3

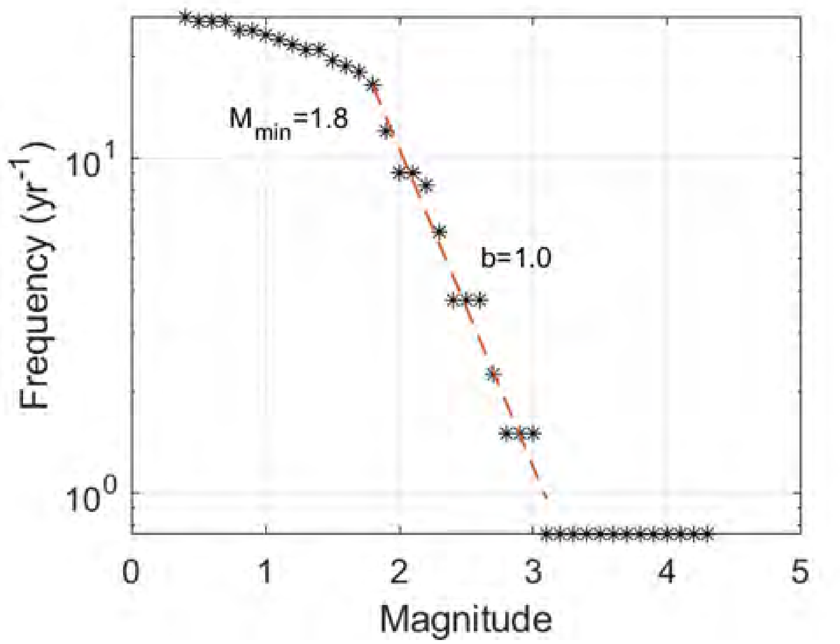


Figure 8. *Gutenberg-Richter plot for events located by the CSRC microseismic monitoring network. The b-value, or negative slope on a semi-logarithmic scale, and the magnitude of completeness (Mmin) are labeled on the best-fitting line through the linear part of the plot.*

Summary

Within parts of the Rome Trough in eastern Kentucky and West Virginia, the deep Rogersville Shale has been tested for oil and gas production. Because of the shale's low permeability, production requires unconventional methodologies—in particular, high-volume and high-pressure hydraulic fracturing. Also, because of the shale's proximity to the crystalline basement and its location within the faulted Rome Trough, however, there is a potential for inducing earthquakes during or following fracture stimulation. Furthermore, the injection of produced wastewater for disposal, the chief culprit of inducing larger-magnitude (up to magnitude 5.8) earthquakes in places such as Oklahoma, Arkansas, and Ohio, continues in the Rome Tough of eastern Kentucky.

To facilitate discrimination between potential future induced earthquakes and natural seismicity, a network of eight sensitive seismic monitoring stations was used to enhance the characterization of natural, background seismic activity in the Rome Trough of eastern Kentucky. This network improved the monitoring sensitivity in the vicinity of wastewater-injection wells and where hydrocarbons from the Rogersville Shale would most likely be produced.

Using real-time recordings from the CSRC seismic monitoring network in tandem with recordings of other temporary and permanent regional seismic stations, a catalog of 39 local earthquakes was developed using a combination of tradition and machine-learning-based techniques. Only three earthquakes occurred in the crust beneath the Rome Trough of eastern Kentucky, none of which were near the region of potential hydrocarbon production from the Rogersville Shale nor could be associated with wastewater-injection wells.

Data and Resources

CSRC monitoring network recordings and metadata are stored at KGS and are available upon request; contact Seth Carpenter. The Kentucky Seismic and Strong-Motion Network, operated jointly by the Kentucky Geological Survey and the University of Kentucky Department of Earth and Environmental Sciences, recordings are continuously archived at Incorporated Research Institutions for Seismology's Data Management Center (IRIS DMC; ds.iris.edu/ds/nodes/dmc) and at the Kentucky Geological Survey (doi:10.7914/SN/KY). Other seismic network data are also available through IRIS DMC.

References

Alsaker, A., Kvamme, L.B., Hansen, R.A., Dahle, A., and Bungum, H., 1991, The ML scale in Norway: Bulletin of the Seismological Society of America, v. 81, no. 2, p. 379–398.

Bao, X., and Eaton, D.W., 2016, Fault activation by hydraulic fracturing in western Canada: Science, v. 354, issue 6318, p. 1406–1409, doi:10.1126/science.aag2583.

Carpenter, N.S., Woolery, E.W., and Wang, Z., 2014, The Mw 4.2 Perry County, Kentucky, earthquake of 10 November 2012: Evidence of the Eastern Tennessee Seismic Zone in southeastern Kentucky: Seismological Research Letters, v. 85, no. 4, p. 931–939, doi:10.1785/0220130221.

Carpenter, N.S., Holcomb, A.S., Woolery, E.W., Wang, Z., Hickman, J.B. and Roche, S.L., 2020. Natural seismicity in and around the Rome Trough, Eastern Kentucky, from a temporary seismic network. Seismological Research Letters, 91(3), pp.1831-1845.

Chapman, M.C., Mathena, E.C., and Snoke, J.A., 2002, Southeastern United States Seismic Network Bulletin: U.S. Geological Survey, Bulletin 36, www.magma.geos.vt.edu/vtso/anonftp/catalog/bul36.pdf.

Ellsworth, W.L., 2013, Injection-induced earthquakes: Science, v. 341, no. 6142, 1225942, doi:10.1126/science.1225942.

Harris, D.C., 2015, Cambrian Rogersville Shale in the Rome Trough, Kentucky and West Virginia: A potential new unconventional reservoir in the Appalachian Basin: American Association of Petroleum Geologists Search and Discovery Article 10787, www.searchanddiscovery.com/pdfz/documents/2015/10764hickman/ndx_hickman.pdf.html.

Havskov, J., and Ottemöller, L., 1999, SEISAN earthquake analysis software: Seismological Research Letters, v. 70, no. 5, p. 532–534.

Herrmann, R.B., and Ammon, C.J., 1997, Faulting parameters of earthquakes in the New Madrid, Missouri, region: Engineering Geology, v. 46, nos. 3-4, p. 299–311.

Herrmann, R.B., Langston, C.A., and Zollweg, J.E., 1982, The Sharpsburg, Kentucky, earthquake of 27 July 1980: Bulletin of the Seismological Society of America, v. 72, no. 4, p. 1219–1239.

Hickman, J.B., Harris, D.C., and Eble, C.F., 2015, Cambrian Rogersville Shale in the Rome Trough, Kentucky and West Virginia: A potential new unconventional reservoir in the Appalachian Basin: American Association of Petroleum Geologists Search and Discover Article 2103714, www.searchanddiscovery.com/abstracts/html/2015/90216ace/abstracts/2103714.html.

Holcomb, A., 2017, Initial microseismic recordings at the onset of unconventional hydrocarbon development in the Rome Trough, eastern Kentucky: Lexington, University of Kentucky, master's thesis, 225 p., doi.org/10.13023/ETD.2017.316.

Holland, A.A., 2013, Earthquakes triggered by hydraulic fracturing in south-central Oklahoma: Bulletin of the Seismological Society of America, v. 103, no. 3, p. 1784–1792, doi:10.1785/0120120109.

Johnson, C.E., Bittenbinder, A., Bogaert, B., Dietz, L., and Kohler, W., 1995, Earthworm: A flexible approach to seismic network processing: IRIS Newsletter, v. 14, no. 2, p. 1–4.

Kentucky Geological Survey, 2014, Induced seismic events in Kentucky: Kentucky Geological Survey, Fact Sheet, 4 p., www.uky.edu/KGS/education/factsheet-InducedSeismicEvents.pdf.

Keranen, K.M., Savage, H.M., Abers, G.A., and Cochran, E.S., 2013, Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence: Geology, v. 41, no. 6, p. 699–702, doi.org/10.1130/G34045.1.

Langenbruch, C., and Zoback, M.D., 2016, How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?: Science Advances, v. 2, no. 11, e1601542, doi:10.1126/sciadv.1601542.

Lienert, B.R., and Havskov, J., 1995, A computer program for locating earthquakes both locally and globally: Seismological Research Letters, v. 66, no. 5, p. 26–36.

Miao, F., Carpenter, N.S., Wang, Z., Holcomb, A.S. and Woolery, E.W., 2020. High-accuracy discrimination of blasts and earthquakes using neural networks with multiwindow spectral data. Seismological Research Letters, 91(3), pp.1646-1659.

National Research Council, 2013, Induced seismicity potential in energy technologies: Washington, D.C., The National Academies Press, 262 p., doi.org/10.17226/13355.

Richter, C.F., 1935, An instrumental earthquake magnitude scale: Bulletin of the Seismological Society of America, v. 28, no. 1, p. 1–32.

Ross, Z.E., Meier, M.A., Hauksson, E. and Heaton, T.H., 2018. Generalized seismic phase detection with deep learning. Bulletin of the Seismological Society of America, 108(5A), pp.2894-2901.

Ross, Z.E., Yue, Y., Meier, M.A., Hauksson, E. and Heaton, T.H., 2019. PhaseLink: A deep learning approach to seismic phase association. Journal of Geophysical Research: Solid Earth, 124(1), pp.856-869.

Ross, Z.E., Cochran, E.S., Trugman, D.T. and Smith, J.D., 2020. 3D fault architecture controls the dynamism of earthquake swarms. Science, 368(6497), pp.1357-1361.

Rubinstein, J.L., Ellsworth, W.L., McGarr, A., and Benz, H.M., 2014, The 2001–present induced earthquake sequence in the Raton Basin of northern New Mexico and southern Colorado: Bulletin of the Seismological Society of America, v. 104, no. 5, p. 2162–2181, doi:10.1785/0120140009.

Skoumal, R.J., Brudzinski, M.R., and Currie, B.S., 2015, Earthquakes induced by hydraulic fracturing in Poland Township, Ohio: Bulletin of the Seismological Society of America, v. 105, no. 1, p. 189–197, doi:10.1785/0120140168.

Sparks, T.N., and Curl, D.C., 2014, Class I and Class II wells in Kentucky (disposal and injection wells): Kentucky Geological Survey, kygs.maps.arcgis.com/home/webmap/viewer.html?webmap=9380ec4940cd46c9b2c65a1160753f6f.

Stein, S., and Wysession, M., 2009, An introduction to seismology, earthquakes, and earth structure: New York, Wiley, 499 p.

Taylor, J., Celebi, M., Greer, A., Jampole, E., Masroor, A., Melton, S., Norton, D., Paul, N., Wilson, E., and Xiao, Y., 2017, EERI Earthquake Reconnaissance Team Report: M5.0 Cushing, Oklahoma, USA earthquake on November 7, 2016: EERI Learning From Earthquakes Program, 25 p.

Weingarten, M., Ge, S., Godt, J.W., Bekins, B.A., and Rubinstein, J.L., 2015, High-rate injection is associated with the increase in US mid-continent seismicity: Science, v. 348, no. 6241, p. 1336–1340, doi:10.1126/science.aab1345.

Wiemer, S., and Wyss, M., 2000, Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan: Bulletin of the Seismological Society of America, v. 90, no. 4, p. 859–869.

Withers, M., Aster, R., Young, C., Beiriger, J., Harris, M., Moore, S., and Trujillo, J., 1998, A comparison of select trigger algorithms for automated global seismic phase and event detection: Bulletin of the Seismological Society of America, v. 88, no. 1, p. 95–106.

Yeck, W.L., Hayes, G.P., McNamara, D.E., Rubinstein, J.L., Barnhart, W.D., Earle, P.S., and Benz, H.M., 2017, Oklahoma experiences largest earthquake during ongoing regional wastewater injection hazard mitigation efforts: Geophysical Research Letters, v. 44, no. 2, p. 711–717, doi.org/10.1002/2016GL071685.

Zoback, M.D., Townend, J., and Grollimund, B., 2002, Steady-state failure equilibrium and deformation of intraplate lithosphere: International Geology Review, v. 44, no. 5, p. 383–401.

g. Task 7.1 – Total organic content (%TOC) analysis of geological samples

By John Hickman, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

One of the major issues encountered while completing unconventional oil and gas wells in Conasauga Group rocks is the extremely heterogeneous distribution of organic material within the shale units. In order for specific geological units to become hydrocarbon source rocks, they must contain sufficient organic material (> 1 wt%) for petrogenesis to occur during burial and thermal maturation. Because hydrocarbons do not tend to migrate through low-porosity shales, the "landing points" of production laterals in unconventional reservoirs need to penetrate the organically "rich" sections to maximize oil and/or gas production from those shales. Therefore, knowing where organic material is concentrated can dramatically change the production results of a well.

Measurements of TOC content are performed on physical samples in a lab, but are not available in situ. This can lead to sampling bias based upon where in the section the sample is taken. To further complicate the issue, existing data indicated that unlike in some younger stratigraphy (i.e. Devonian Shales and others), the optical qualities (color and/or darkness) of Conasauga geological samples had no bearing on its organic content analysis results. Therefore, this project aimed to produce one or more profiles of "continuous" measurements (i.e., on every depth interval) that could act as a pseudo-log of TOC content through the Conasauga shales which could be displayed in cross sections alongside traditional geophysical logs.

In Task 3 (see above), KGS and WVGES staff compiled all legacy TOC data in their respective archives on the Conasauga Group (Figure 1), resulting in a total of 537 data points. These data were imported into the respective wells within an IHS Petra software project. With these point values displayed at their sampled depth along well-based cross sections, "holes" in the data within possible UOG reservoir shales in the Conasauga Group were identified (Figure 2). The CSRC sampling targeted these gaps in the TOC well data, focusing on wells within the core of the Rogersville Shale play area; Johnson and Lawrence Counties in Kentucky, and Wayne and Lincoln Counties in West Virginia.

Following the identification of an organically-rich interval (and its geophysical log character) within the Rogersville Shale (see yellow highlighted interval in Figure 2), CSRC attempted to sample the equivalent interval/bed in older wells, including outside of the core area in an effort to map out the lateral extent of the potential source rock.

WVGES and KGS sampled well cuttings across the identified "sweet spots" within individual wells and sent them to the KGS Lab for TOC analysis. This included cuttings from 105 depth intervals across five West Virginia wells: 4701302503 (Exxon Gainer-Lee), 4703501366 (Exxon McCoy, Stalnaker), 4704301469 (Exxon McCormick), 4705900805 (Columbia Gas 9674T), and 4709901572 (Exxon Jay P Smith). KGS sampled 192 footages for additional TOC sampling from 19 KY wells. Although many wells had limited cuttings available in the desired interval, and total of 297 new samples were acquired for TOC analysis at the KGS Laboratory by Jason Backus. These results further permitted the selected sampling of ONLY organically-rich samples for the follow-up tests for thermal maturity (%Ro, Task 7.5) and pyrolysis (RockEVAL, Task 7.9).

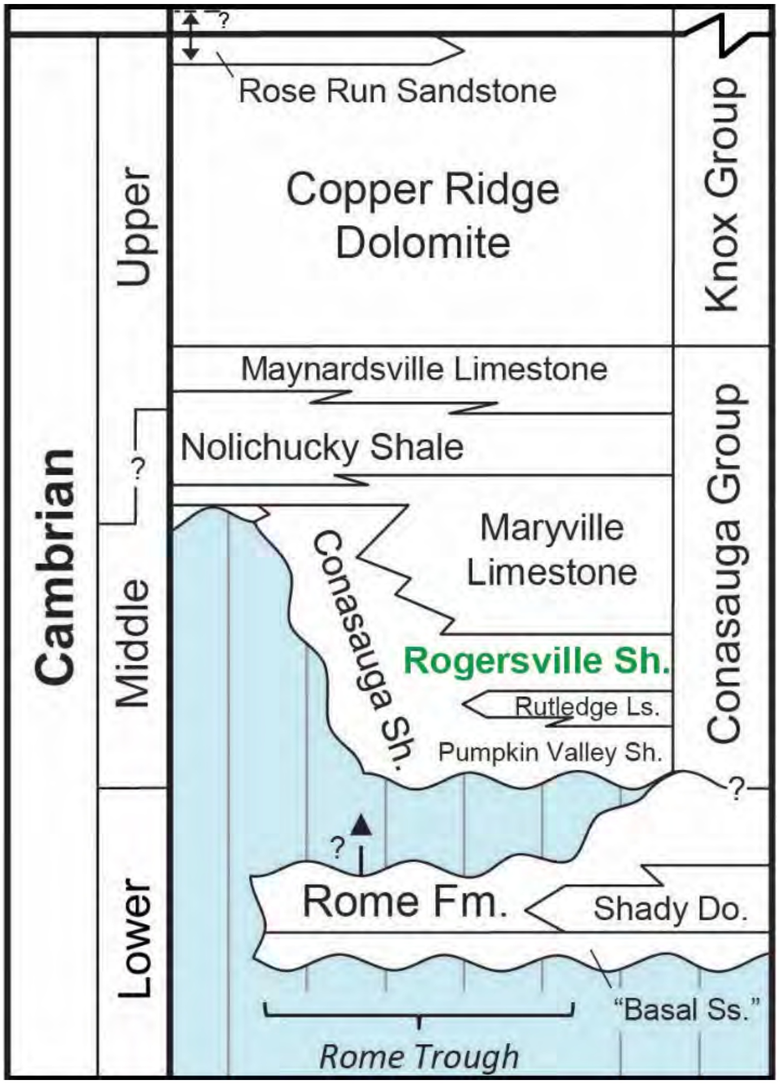


Figure 1. Stratigraphic column for Cambrian rocks in the Rome Trough, including the Conasauga Group (modified from Greb 2017).

During this process, CSRC also identified an apparent discrepancy between some cuttings-derived %TOC values versus core-derived %TOC data within the same well. Unfortunately, because of the shortened research term of this project, we were unable to determine whether this is an effect of the oil-based drilling mud on the cuttings, or if it is from dilution of organic matter distributed across the whole sampled interval (usually 10 feet), see Figure 3.

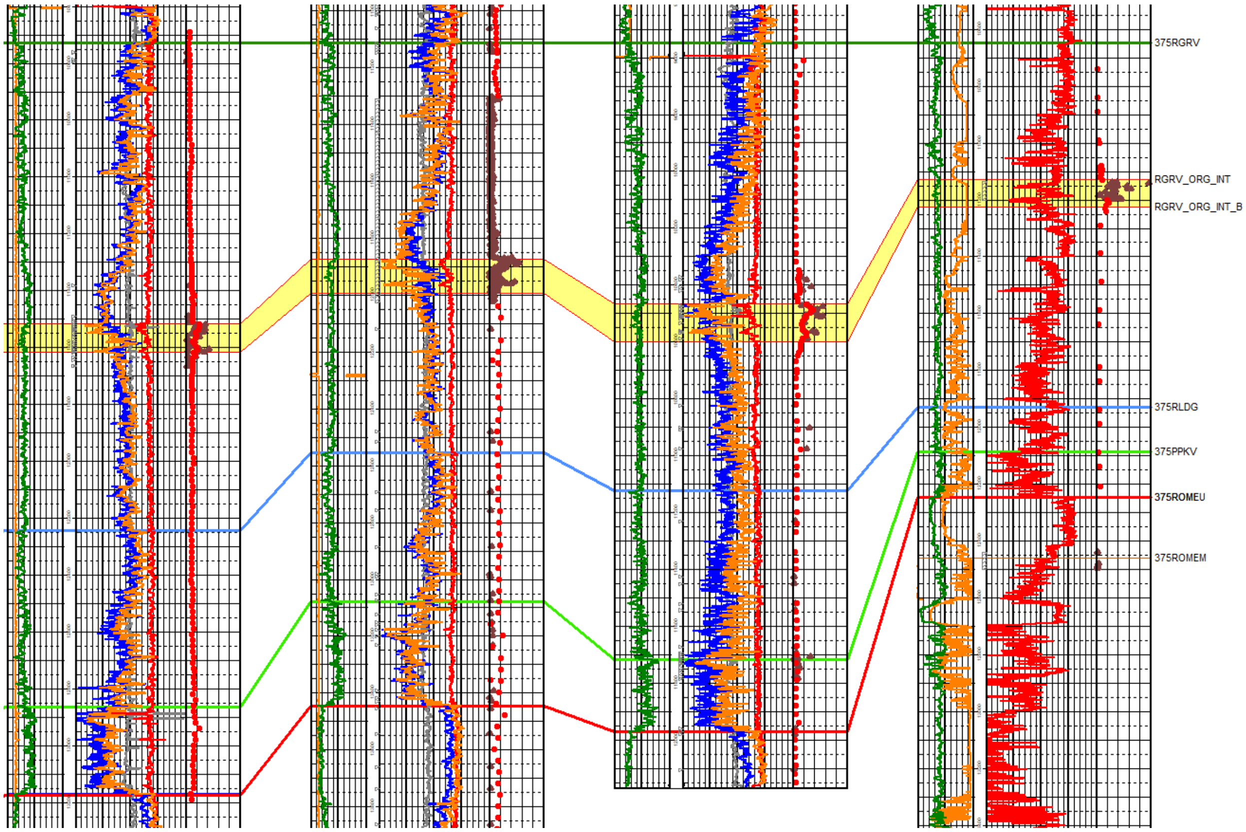


Figure 2. Well-based stratigraphic cross section (datum is the top of Rogersville Shale) through Lawrence County, Kentucky (left) to Wayne County, West Virginia (right). Each well has two columns of geophysical logs displayed, with a third column (rightmost for each well) of TOC data. Brown symbols mark depths of core samples, and red symbols mark depths of cuttings samples (10 ft intervals). The TOC scale is 0-5%, increasing to the right.

<u>Conclusions (preliminary)</u>

Throughout the Conasauga Group in the Rome Trough, the only rocks that appear to have sufficient organic content to produce hydrocarbons (> 1 wt% TOC) are within the Rogersville Shale. Furthermore, although the Rogersville Shale approaches 1,750 feet thick in Johnson and Lawrence Counties in Kentucky, the "sweet spot" of organic richness is less than 140 feet thick (Figure 4). All samples analyzed were less than 5% TOC, including those within the organic zone. Based upon the bioturbation and sedimentary features visible within the Rogersville whole cores, it appears that the deposition of the Rogersville Shale was in a fairly shallow, well oxygenated environment. Such settings are not conducive to organic preservation, probably leading to the dramatically low TOC content that exists for most of the section. The end result appears to be a relatively thin, low grade source rock within a much larger shale body resulting in limited producible volumes of hydrocarbons. Unfortunately, this large shale body also contains a large fraction of expandable clays, which has led to hole collapses during drilling and logging, and can also impede large frac propagation during completion work.

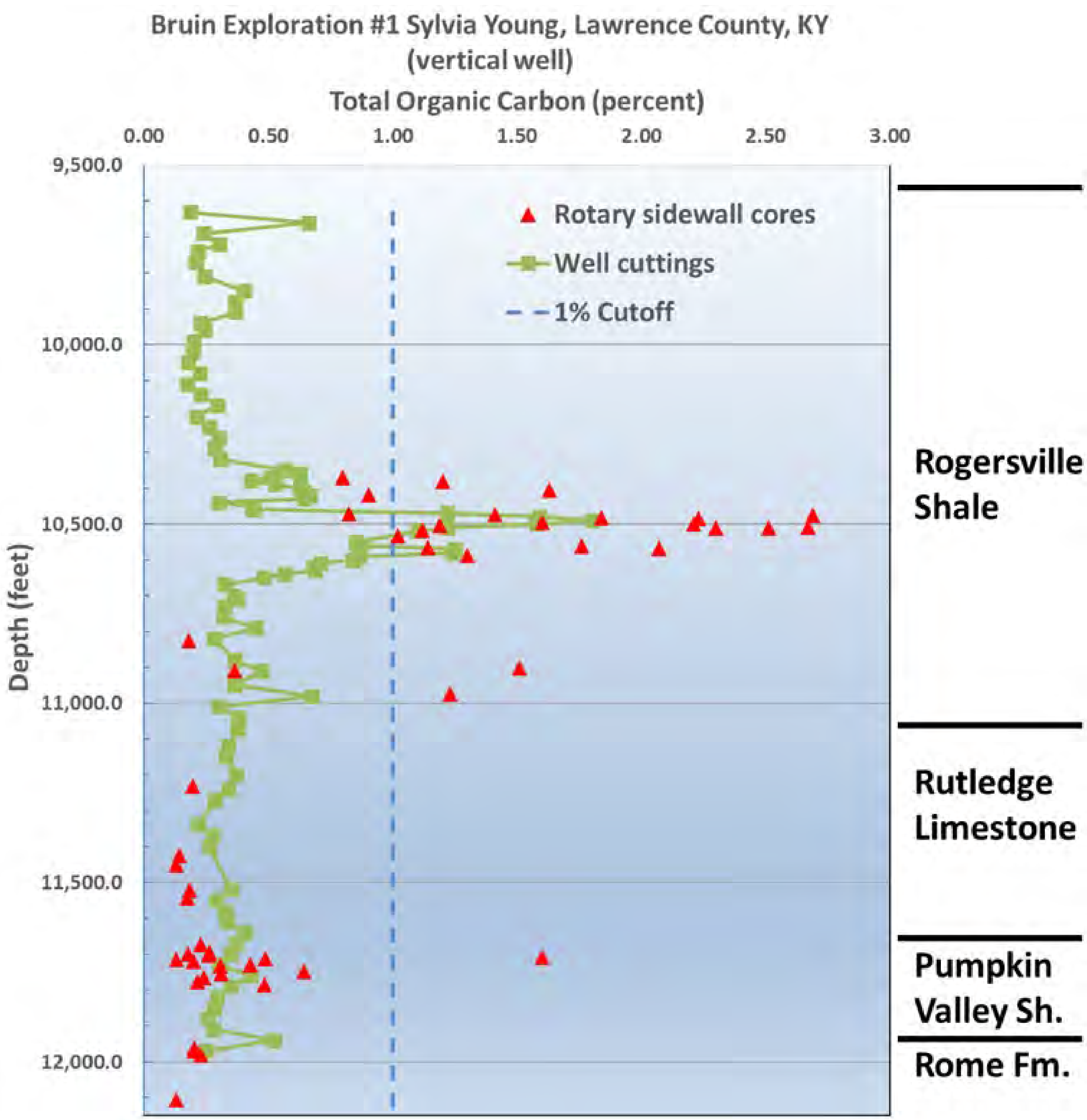


Figure 3. A plot of total organic carbon (TOC) vs. depth for the Bruin (Cimarex) #1 Young well. TOC is highest in a 250' zone near the middle of the Rogersville Shale. Also note that well cuttings tend to underestimate TOC compared with sidewall cores. (Data contributed by Cimarex) The blue dashed line represents the theoretical minimum TOC needed to produce hydrocarbons.

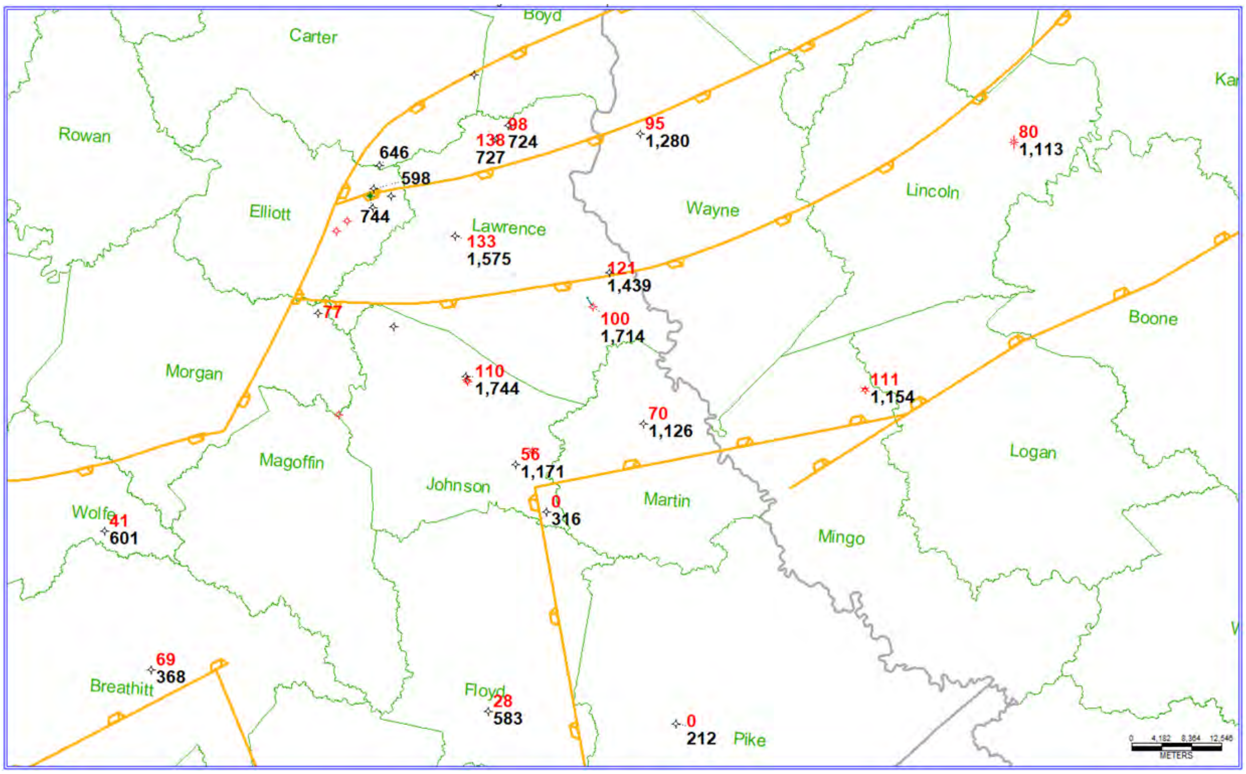


Figure 4. Map of deep wells in eastern KY and southwestern WV. Black values next to well symbols indicate thickness of Rogersville Shale in feet, red numbers indicate thickness of organic-rich zone. Tan lines represent simplified basement fault trends.

References

Greb, SF, 2017, Kentucky Stratigraphy. Kentucky Geological Survey, Series 12, Map and Chart 211, 1 sheet.

h. Task 7.2 – X-ray Diffraction (XRD) lab analysis of sample mineralogy*

By Amy Weislogel, PhD

West Virginia University – Department of Geology & Geography

Morgantown, Wva.

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 3 months of work out of the expected and budgeted 18-month research plan.)

Introduction

Dr. Weislogel performed work on Subtask 7.2 that involved XRD mineralogy analysis of Conasauga Group units from 3 new wells. In addition, Dr. Weislogel reports initial results from petrographic analysis, XRF compositional analysis, and carbon isotope analysis of the Rogersville Shale from the Exxon Jay Smith #1 well.

Methods

Due to COVID-19 restrictions, WVU's XRD facilities were unavailable for sample analysis as originally planned in Subtask 7.2, and the work plan was modified to observe pandemic safety protocols. In this modified work plan, the Kentucky Survey personnel obtained 56 samples of cuttings collected in 10-ft intervals from Conasauga Group units from 3 wells: Exxon 1 Banks, Orville, Ashland Exploration 1 Williams, E and Hay Exploration 1 Blue Ribbon Coal (Fig. 1; Table 1). These samples were analyzed by Core Labs to determine XRD mineralogy.

Table 1. *New wells sampled for XRD mineralogy*

Well	Latitude	Longitude	County, State	Interval Sampled
Exxon #1 Banks, Orville	37.7086018	-83.3677789	Wolfe Co., KY	8,610-9,860 ft
Ashland Exploration #1 Williams, E	37.8612777	-83.0025909	Johnson Co., KY	9,330-10,600 ft
Hay Exploration #1 Blue Ribbon Coal	37.8201528	-82.6967543	Johnson Co., KY	10,500-10,960 ft

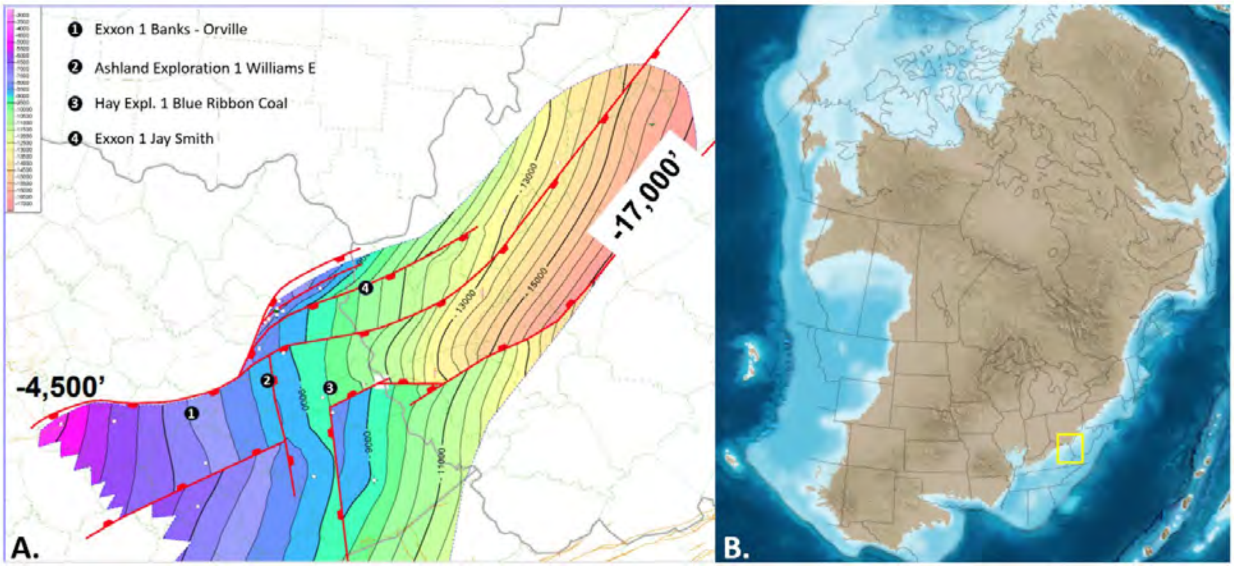


Figure 25. A. Location of the 4 wells in the study area analyzed in this report, shown on the Rogersville Shale structure map of Hickman et al. (2015). B. Paleogeography of North America during the Middle Cambrian showing location of the study area; image from Blakey, Colorado Plateau Geosystems.

<u>Results</u>

Twenty-three samples characterize the Exxon 1 Banks-Orville well in Wolfe Co., KY, and indicate overall quartz-rich and clay-rich mudstone (Table 2), including one apparent chert interval at 9410-9420 ft (Fig. 1). Overall, the lower section is more clay-rich and feldspar abundance increases upsection (Fig. 2). Twenty-four samples characterize the Ashland Exploration # Williams E well, located in western Johnson Co., KY. These samples show a greater abundance of calcite compared to the Orville well, and calcite abundance increases upsection as clay/phyllosilicate and framework silicate abundance decrease. Nine samples characterize the Hay Exploration #1 Blue Ribbon Coal well, located in eastern Johnson Co., KY, and show similar mineralogical abundances as the nearby Ashland Exploration Williams E samples.

The Ashland and Hay wells are located ~20-35 miles toward of the Exxon well along the northeastern strike of the Rome Trough, and may be more distal to a point source of silicilastic influx that is responsible for the greater abundance of quartz and clay observed in the Exxon well. This hypothesis will be further scrutinized through comparison with other legacy XRD data available from other wells in the region and integration into petrophysical and regional correlation model developed by the Kentucky Geological Survey. From this integration, the influence of siliciclastic input from uplifted structural highlands on lithological character of the Conasauga Group units will be assessed.

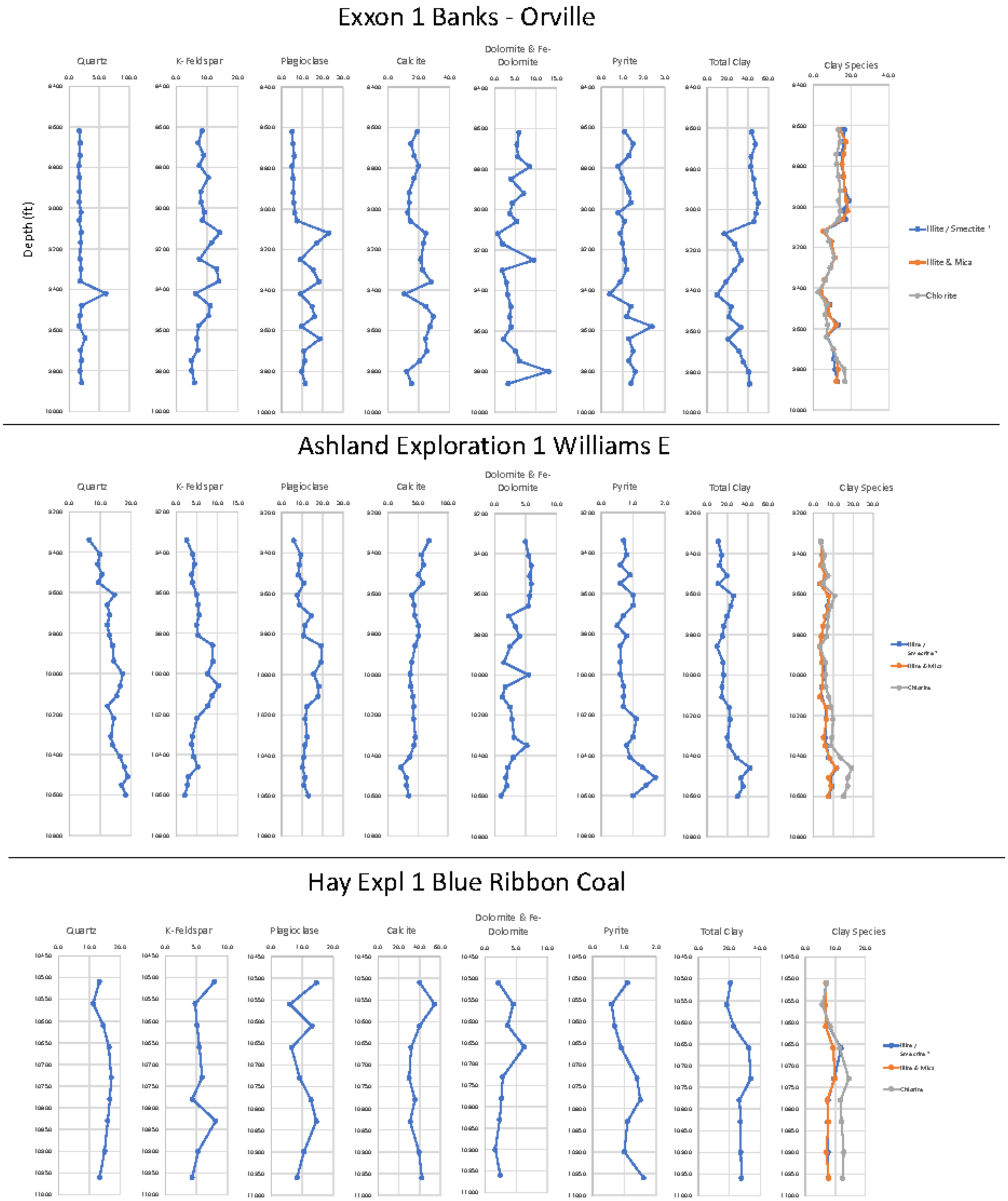


Figure 2. *XRD mineralogy results from 3 new wells analyzed in Q1 2021.*

Table 2. *Average XRD mineralogical abundances for the three newly sampled wells.*

	Average Whole Rock Mineralogy (Weight %)							Average Clay Mineralogy (Weight %)		
	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite & Fe-Dolomite	Pyrite	Total Clay	Illite / Smectite *	Illite & Mica	Chlorite
Exxon 1 Banks - Orville	20.3	8.8	10.8	19.5	4.8	1.2	34.6	11.9	11.9	10.8
Std. Dev	9.1	2.6	5.2	5.6	2.8	0.4	11.9	4.3	4.3	3.8
Ashland Expl. Williams E	13.8	5.3	12.1	43.7	3.5	0.9	20.7	6.0	5.7	8.9
Std. Dev	3.2	2.3	3.7	10.4	1.7	0.3	8.4	2.1	2.1	4.4
Hay Expl. 1 Blue Ribbon Coal	14.8	5.7	10.6	38.2	3.1	1.1	26.4	8.1	7.7	10.7
Std. Dev	1.9	1.4	3.3	7.6	1.5	0.3	5.1	1.7	1.1	2.9

i. Task 7.3 – X-ray Fluorescence (XRF) elemental analysis in lab*

By Amy Weislogel, PhD

West Virginia University – Department of Geology & Geography

Morgantown, WVa.

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 3 months of work out of the expected and budgeted 18-month research plan.)

<u>XRF Analysis</u>

WVU collected 40 samples from the Exxon # 1 Jay Smith Well located in Wayne Co., West Virginia using a Dremel rotary tool and a chisel. Approximately ~10 g of sample was collected and divided into 2 aliquots of 5g each. Sample locations were chosen to characterize the overall elemental profile of the core at a resolution ranging from .5-1 ft. XRF analysis of 40 samples of the Exxon Jay Smith #1 well in Wayne Co., WV, was performed by Hamilton Analytic Lab to determine major and trace element abundances. Rock chips were ground in a swing mill with tungsten carbide surfaces for 2 minutes, and 3.5 g of the sample powder is weighed into a plastic mixing jar with 7.0 g of pure $Li_2B_4O_7$ and mixed for ten minutes. The mixed powders are emptied into graphite crucibles, which were placed on a silica tray and

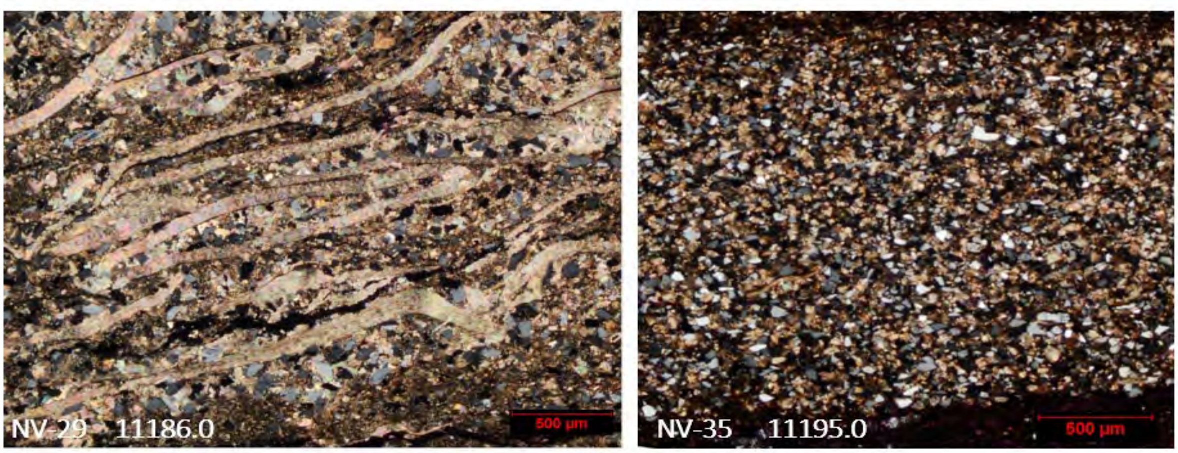


Figure 1. *Photomicrographs of thin-sections examined for petrographic analysis. A. Abundant large trilobite fragments within a silt to very fine-grained sandstone interval. B. Very fine-grained sandstone stringer present in clay-rich mudstone. C. Typical clay-rich mudstone with silt grains, carbonate cement and some sedimentary organic matter.*

loaded into a muffle furnace to produce a glass bead. Each bead was reground in the swingmill for 35 seconds, and the glass powder again was placed in graphite crucibles and refused for 5 minutes. Following the second fusion, the beads lower flat surface is ground on 600 silicon carbide grit, finished briefly on a glass plate (600 grit with alcohol) to remove any metal from the grinding wheel, washed in an ultrasonic cleaner, and then rinsed in alcohol and wiped dry. Finished beads are analyzed using a 2.5 kW Thermo-ARL PerformX spectrometer. Measurements are calibrated and compared to two beads each of nine USGS standard samples (PCC- 1, BCR- 1, BIR- 1, DNC- 1, W-2, AGV- 1, GSP- 1, G-2, and STM-1) as well as two beads of pure quartz. These 40 samples will also be analyzed for trace and rare earth element composition via ICP-MS analysis by Hamilton Analytic Lab.

XRF, Thin-section Petrography and Carbon Isotope Geochemistry Results

Forty samples from the Exxon #1 Jay Smith reveal strong positive correlations in abundance of Al_2O_3 ($r^2 = 0.59$) and K_2O ($r^2 = 0.51$) with SiO_2 and moderate positive correlations in abundance of TiO_2 ($r^2 = 0.26$), Na_2O ($r^2 = 0.34$), and P_2O_5 ($r^2 = 0.33$) with SiO_2, (Plate 1). These suggest influx of clay and orthoclase feldspar, and to a lesser extent rutile, plagioclase feldspar and apatite were associated with an influx of quartz and so are primarily detrital in origin. In contrast, CaO abundances show a very strong negative correlation with SiO_2, (-0.86) and indicates deposition of carbonate-dominated lithofacies corresponds to a decrease in detrital quartz. Other oxides, including MnO, MgO and Fe_2O_2 show very weak (<0.2) positive correlation with SiO_2; these oxides are overall present in very low abundances (7-<.2 wt. %), and likely reflect diagenetic mineralogy but also possibly may indicate conditions of bottom water oxygenation that can be investigated further in concert with trace and rare earth elemental abundances obtained by ICP-MS analysis.

Thin-section review of the Rogersville Shale from the Exxon Jay Smith well reveals 2 primary facies: mudstone and mudstone with very fine-grained sandstone interbeds/ interlaminations. In some cases, the sandstone contains abundant trilobite fragments (Fig. 1A), and sandstone laminations range from >2 cm-thick to mm-thick (Fig. 1B). The remaining lithology is primarily phyllosilicate-dominated mudstone with rare framework silicate silt to very fine sand grains and some carbonate cement and sedimentary organic matter (Fig. 1C). Discrimination of major element geochemistry by facies (Plate 1) does not indicate substantial facies control on geochemical abundances. Therefore, these results indicate the increase in carbonate is linked to the abundance of fragments of shell material from mainly trilobites, which form as intrabasinal clasts that can be present in both clay-dominated mudrock facies as well as mudrock with interbeds and interlaminae of silt/very fine-grained sand. The West Virginia Geologic and Economic survey has obtained continuous XRF analysis of the Exxon #1 Jay Smith core, and we plan to evaluate those results along with thin-section petrography to test this model further.

Forty samples analyzed for carbon isotopic composition of sedimentary organic matter yield $\delta^{13}C$ values ranging from -15.3 to -41.3‰., with a median $\delta^{13}C$ value of -33.7‰ (Fig. 2); this is around a -4 to -6‰ difference from $\delta^{13}C$ values of the overlying Nolichucky and Eau Claire Fm. Of eastern Kentucky analyzed by LeRoy and Gill (2019), which range from -29 to -26‰. Results from the Rogersville are similar to values observed for sedimentary organic matter formed during the Drumian Isotopic Carbon Excursion (DICE; Ahlberg et al., 2009; Li et al. 2020). If this is confirmed with further work, these results will constrain the depositional age of the Rogersville Shale to the Drumian at ~504 Ma, and will signify that this highly negative carbon isotopic excursion can be used as a correlation tool for identifying age-equivalent deposits across the Rome Trough.

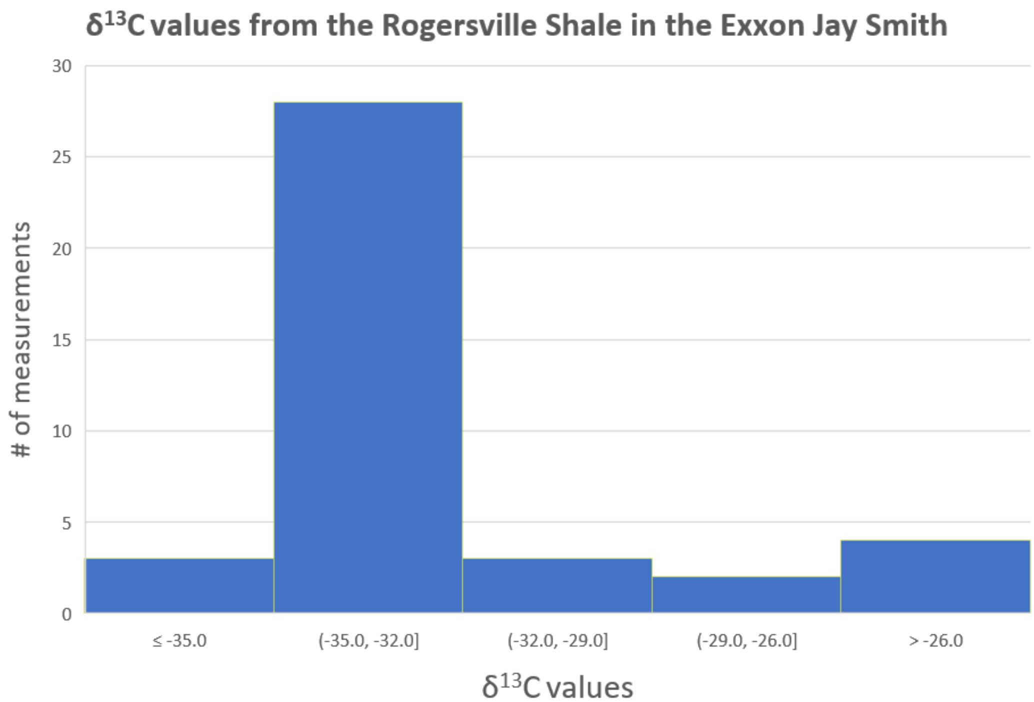


Figure 2*. Carbon isotopic composition of sedimentary organic matter from the Rogersville Shale in the Exxon #1 Jay Smith well yield δ13C values ranging from -15.3 to -41.3‰., with a median δ13C value of -33.7‰. These values are 4 to 6‰ lower than δ13C values of the overlying Nolichucky and Eau Claire Fm.*

<u>References</u>

Ahlberg, P.E.R., Axheimer, N., Babcock, L.E., Eriksson, M.E., Schmitz, B. and Terfelt, F., 2009. Cambrian high-resolution biostratigraphy and carbon isotope chemostratigraphy in Scania, Sweden: first record of the SPICE and DICE excursions in Scandinavia. Lethaia, 42(1), pp.2-16.

Chen, R. and Sharma, S., 2016. Role of alternating redox conditions in the formation of organic-rich interval in the Middle Devonian Marcellus Shale, Appalachian Basin, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *446*, pp.85-97.

Hickman, J., Harris, D. and Eble, C., 2015, June. Cambrian Rogersville Shale in the Rome Trough, Kentucky and West Virginia: A potential new unconventional reservoir in the Appalachian basin. In *AAPG Annual Convention and Exhibition*.

LeRoy, M.A. and Gill, B.C., 2019. Evidence for the development of local anoxia during the Cambrian SPICE event in eastern North America. Geobiology, 17(4), pp.381-400.

Li, D., Zhang, X., Zhang, X., Zhu, H., Peng, S., Sun, L. and Shen, Y., 2020. A paired carbonate–organic $\delta^{13}C$ approach to understanding the Cambrian Drumian carbon isotope excursion (DICE). Precambrian Research, 349, p.105503.

j. Task 7.4 – Portable XRF of whole and rotary-sidewall cores*

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 3 months of work out of the expected and budgeted 18-month research plan.)

Part 1 – WVGES pXRF Research

Phillip Dinterman and Bethany Royce

West Virginia Geologic and Economic Survey

Morgantown, WVa.

Introduction

WVGES examined the Rogersville portion of the Exxon Jay P Smith #1 (API #4709901572) well from Wayne County, West Virginia. This well is located at decimal degree coordinates (NAD83) latitude 38.221803, longitude -82.534439 and UTM coordinates easting 365683.3 and northing 4231537.9. This well was a deep test that was drilled to the Precambrian in 1974 with a total vertical depth of 14,625 feet. WVGES maintains a portion of the core over the Rogersville interval from 11,146-11,200 feet. This core was examined in the past by various entities and exhibited several elevated TOC values; one in excess of 4%, though repeatability of this higher TOC values has been difficult. WVGES examined this core for permeability and portable XRF (pXRF).

Methods

Initial inspection of the Smith 1 Rogersville core revealed several problems. Measured core depths did not match the top/bottom markers written on the box; there were parts of the core that were not correctly oriented stratigraphically and had to be rotated; there were missing pieces of core that were replaced by crumbled newspaper spacers with no indication of the actual amount of core that was missing. The core had been sliced into thirds and, in some intervals, less than a third, which made it difficult to clamp into the permeameter apparatus. There was also no consistency as to which splits of core had been received or with core markings, which made it difficult to reconstruct the actual depths. The depths used for the XRF analysis were rudimentary and referenced to the top markers on the box to denote the starting point of each slot, which is why there is a box and slot numbers associated with the depths. While using the permeameter, it was necessary to reconstruct depth and orientation based on sedimentary structures in the core.

Permeameter

641 permeability measurements were taken on the Smith 1 core using a CoreLab™ PPP_250 Portable Probe mini-permeameter. The experimental permeability was determined by the unsteady state method of

Honarpour and Mahmood (1988) where pressure decay was measured as a function of time to compute Kgas.

Injected gas used was air at ambient temperatures and initial pressures of 28-35 psi. Measurements include observations of core (fossils, fractures, matrix), depths, and vertical and horizontal permeability values. The process involved revising the depths of the core, spacing measurements to every half foot, and recording observations and measurements into an Excel spreadsheet.

XRF

Semiquantitative X-ray fluorescence (XRF) spectroscopy was used to determine bulk elemental concentrations. Measurements were taken every tenth of a foot or at lithological changes on the Smith 1 core using a Bruker TRACER 5i pXRF spectrometer equipped with a SDD graphene window detector and Rh X-ray tube. 1357 measurements were analyzed at 90/180 second phase intervals with air under an 8mm spot window.

Results – Permeameter

The odd shape of the core made it extremely difficult to adapt to our permeameter. The core is slabbed into thirds. Not only was a customized wooden jig required to hold the core for permeability measurements, but the degradation of the core’s material made it difficult to get accurate measurements, since horizontal permeability measurements would often split any laminations in the core during or after air had been injected. Horizontal and vertical permeability were both measured with the vertical permeability being the most reliable since it seldom produced damage to the core during the measurement taking process. Permeability measurements show a trend relatively close to zero. Higher permeability points are probably related to the degradation of core material.

Results – XRF

Given what has been visually observed and through core descriptions it is reasonable to assume Ca reflects the biogenic content, whereas, Si, K, and Al likely represent the flux of siliciclastic sediment via weathering and sediment transport processes. The main elements observed in this core were Al, Ca, Fe, K, S, and Si. The main trace elements observed in the core were Ba, Sr, and Zr. Observations in the siliciclastic faction of the data from Si/Al show a steady supply of terrigenous sediment that increases up section. Carbonate production is shown to have steady accumulation but decreases up section. Normalizing the Ca with Al or Si three peaks of carbonate production around depths of 11,147, 11,164, and from 11,180-11,190 feet are observed. Fossil accumulations at these intervals are also high as well as Mn/Al peaks which may indicate changes in oxygenation levels. This high-resolution elemental analysis of the Smith 1 core allows future paleoclimate reconstructions such as productivity and oxygenation events to be studied further.

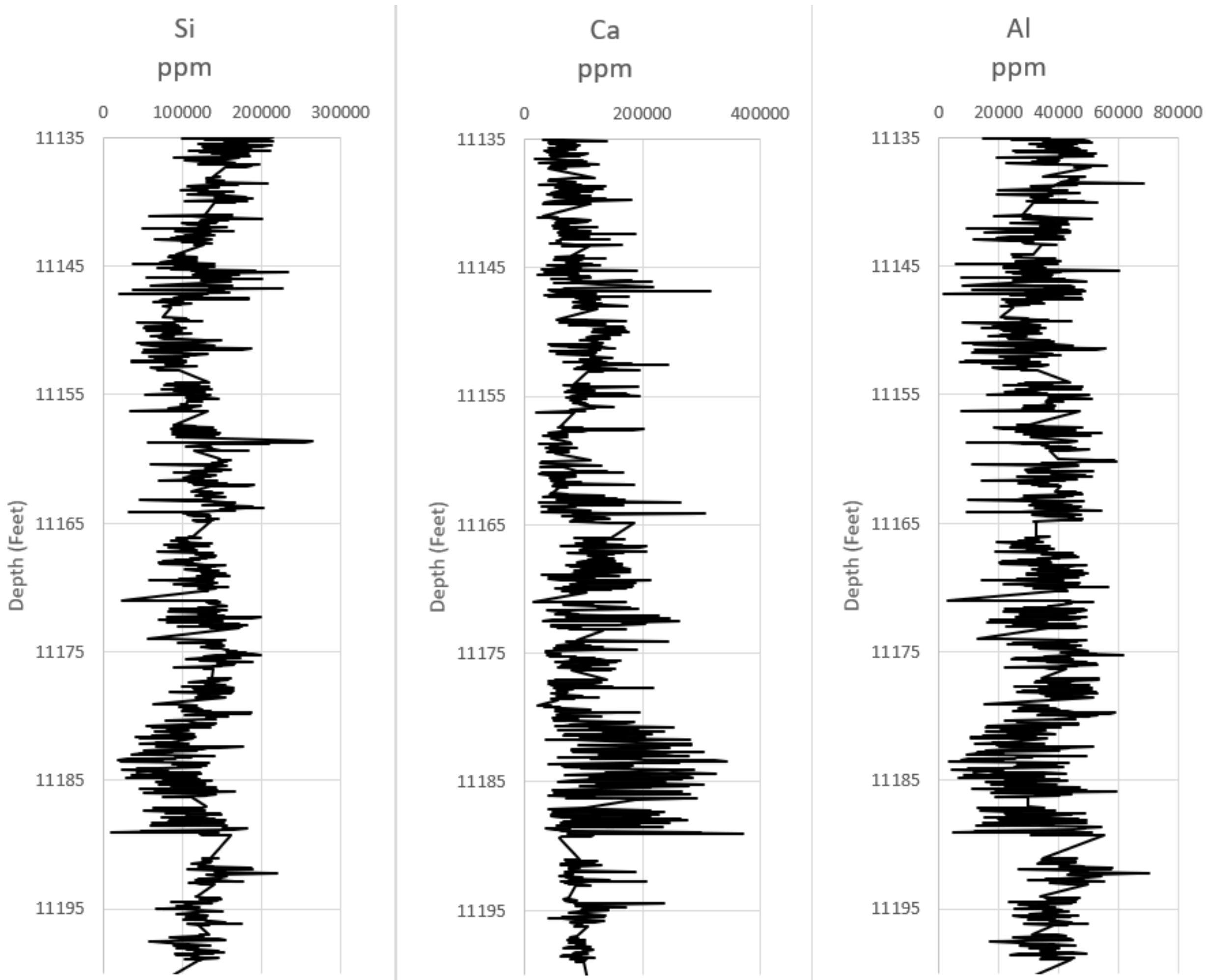


Figure 1*. Al and Si covaries as a constant influx to the system which is out of phase with Ca.*

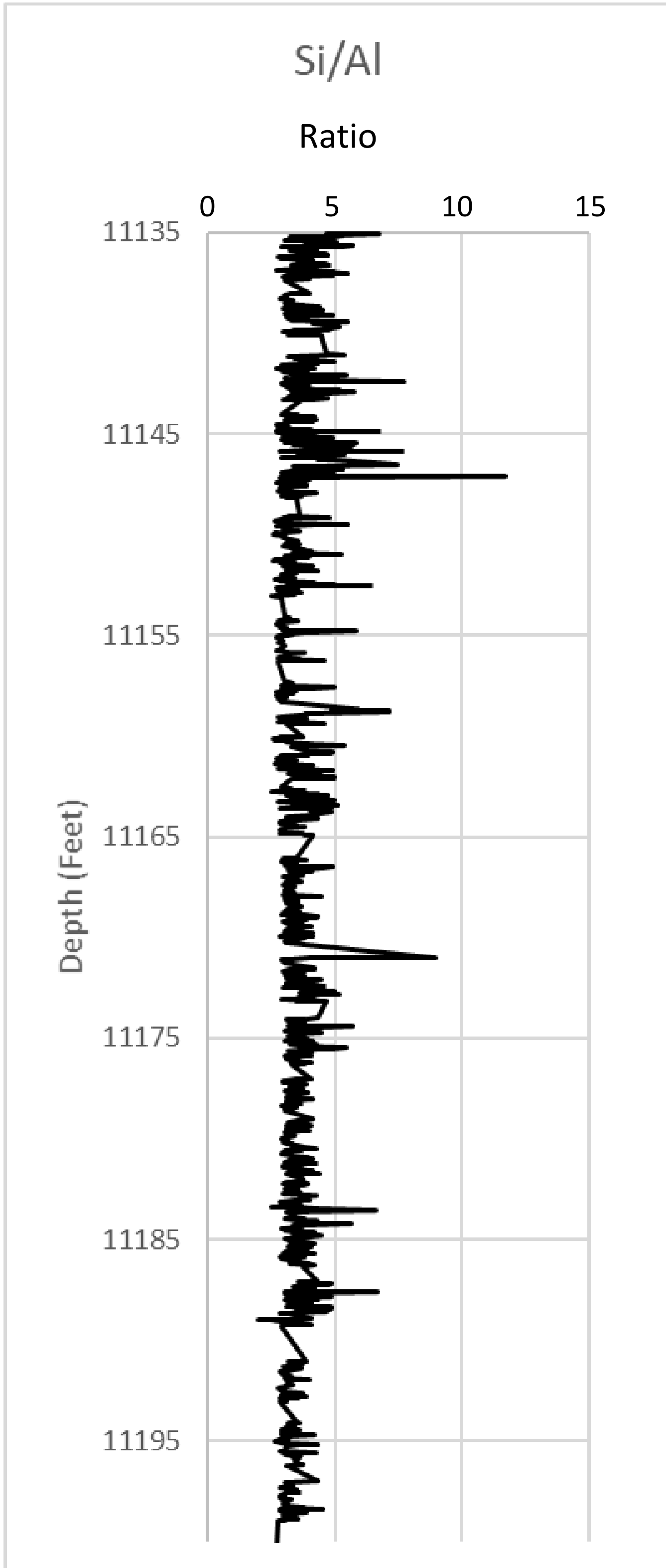


Figure 2. *Si/Al has been used to understand detrital influx.*

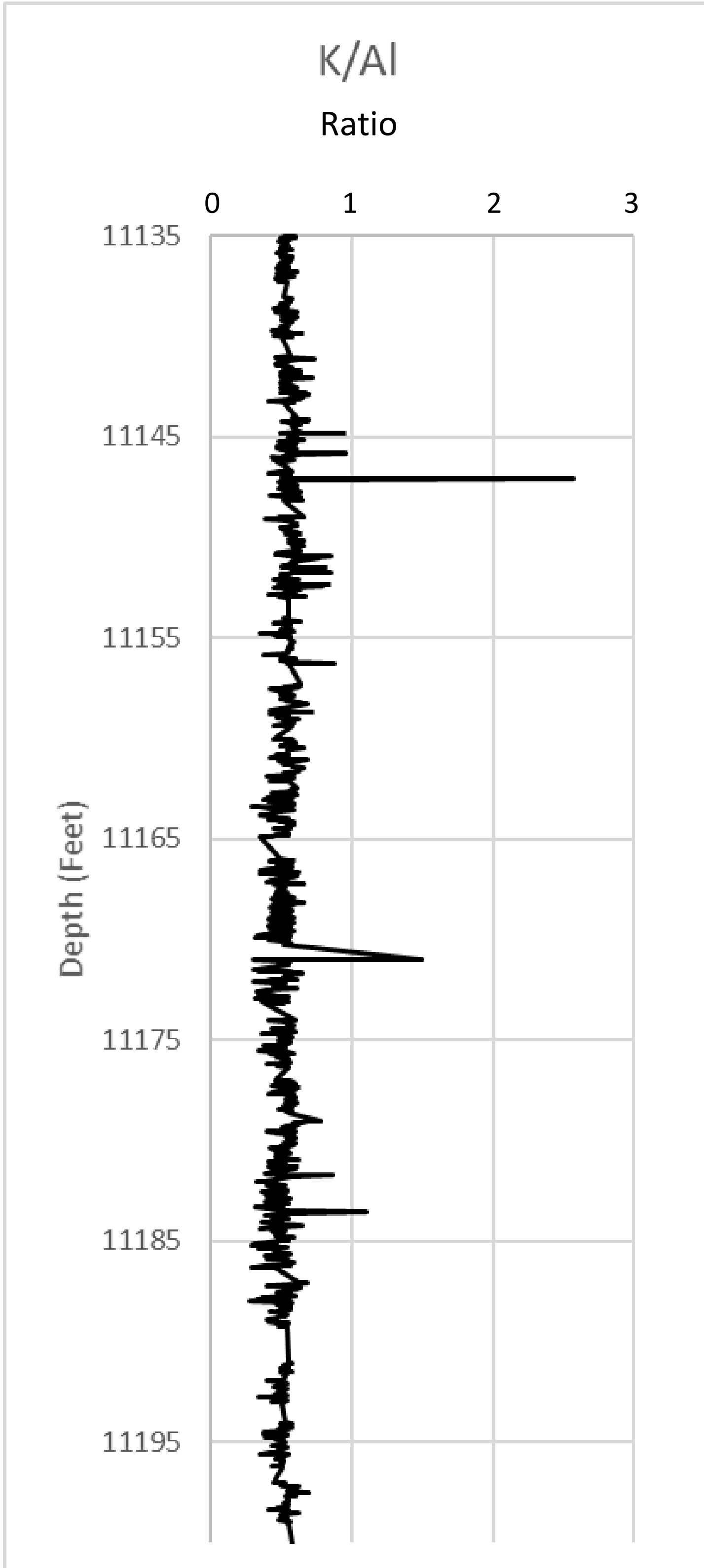


***Figure 3**. K/Al provides information on the abundance of illite and micas versus other clays.*

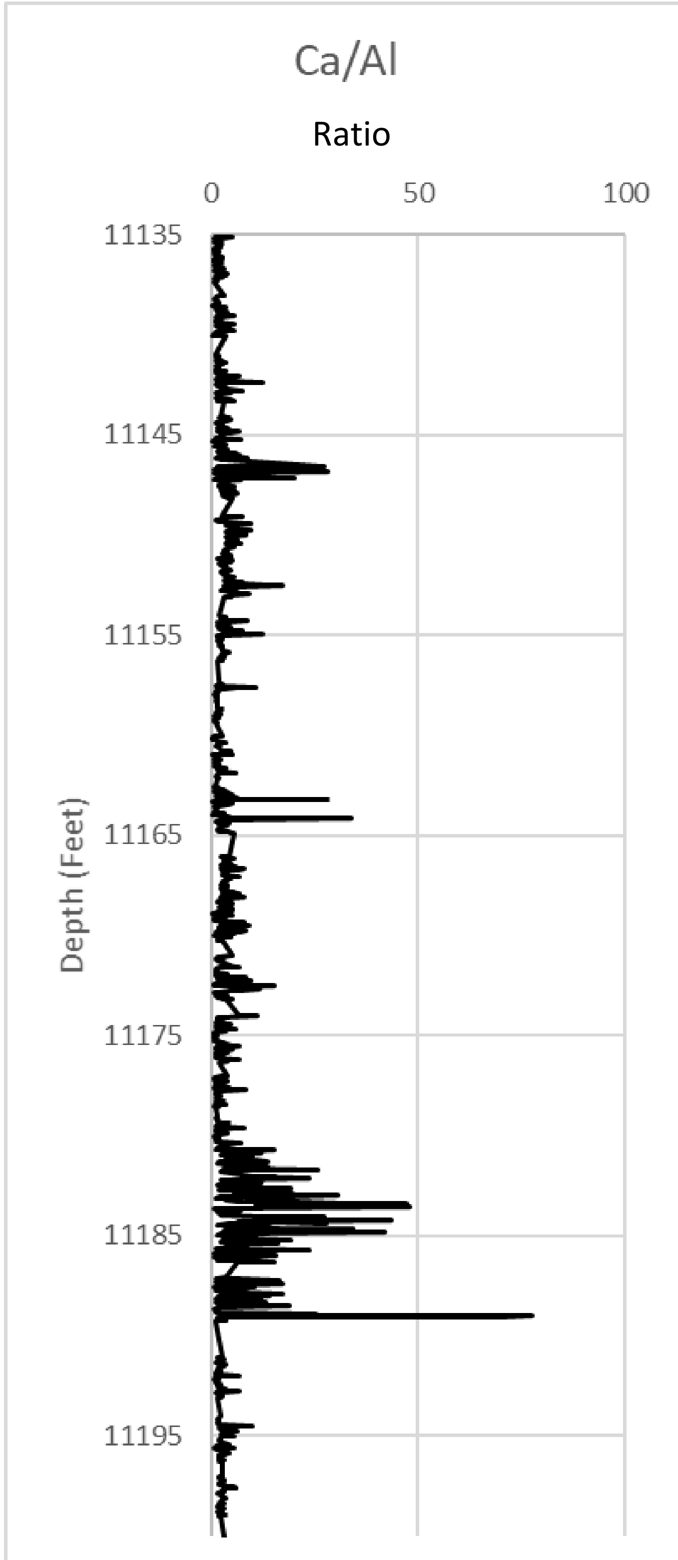


Figure 4. *Ca/Al is approximate amounts of calcium carbonate versus clays and feldspar.*

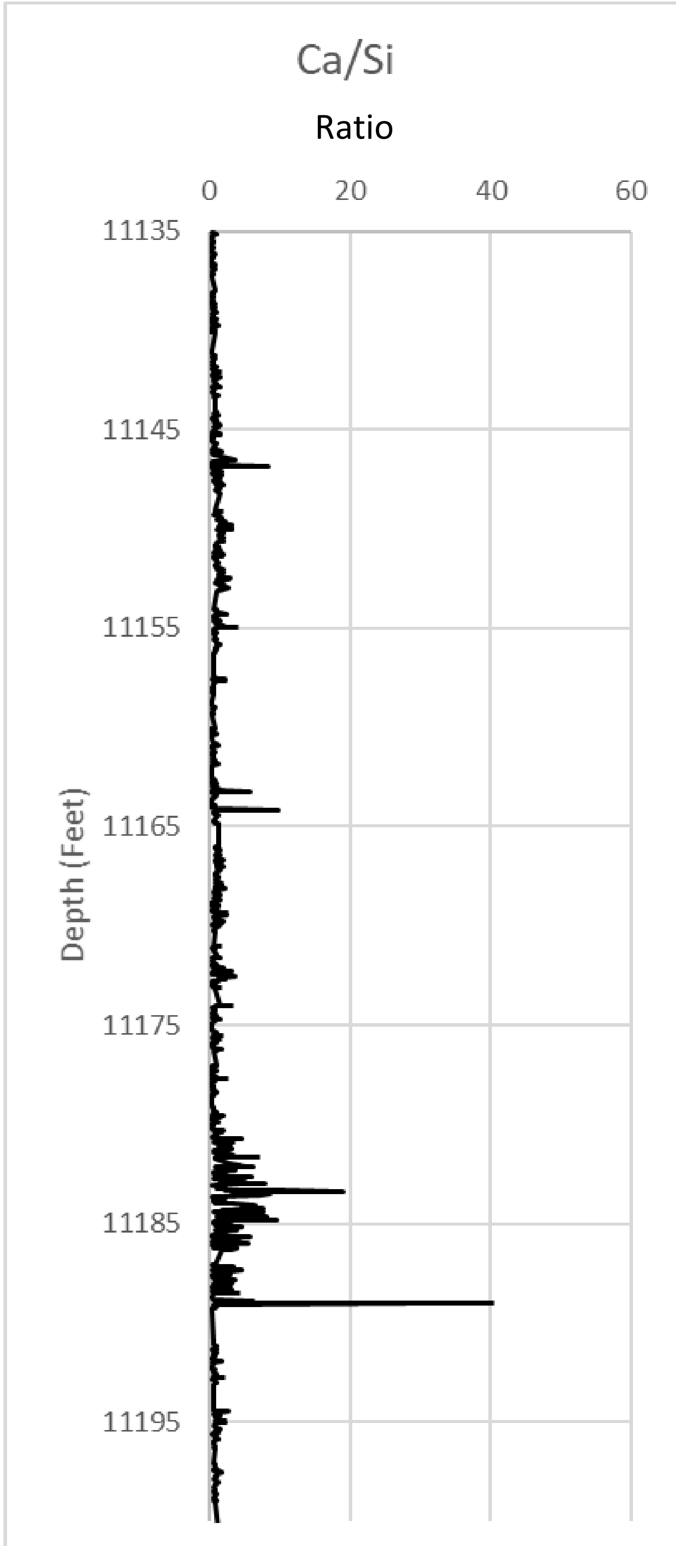


***Figure 5**. Ca/Si, provides information on relative abundance of calcium carbonates versus silicates.*

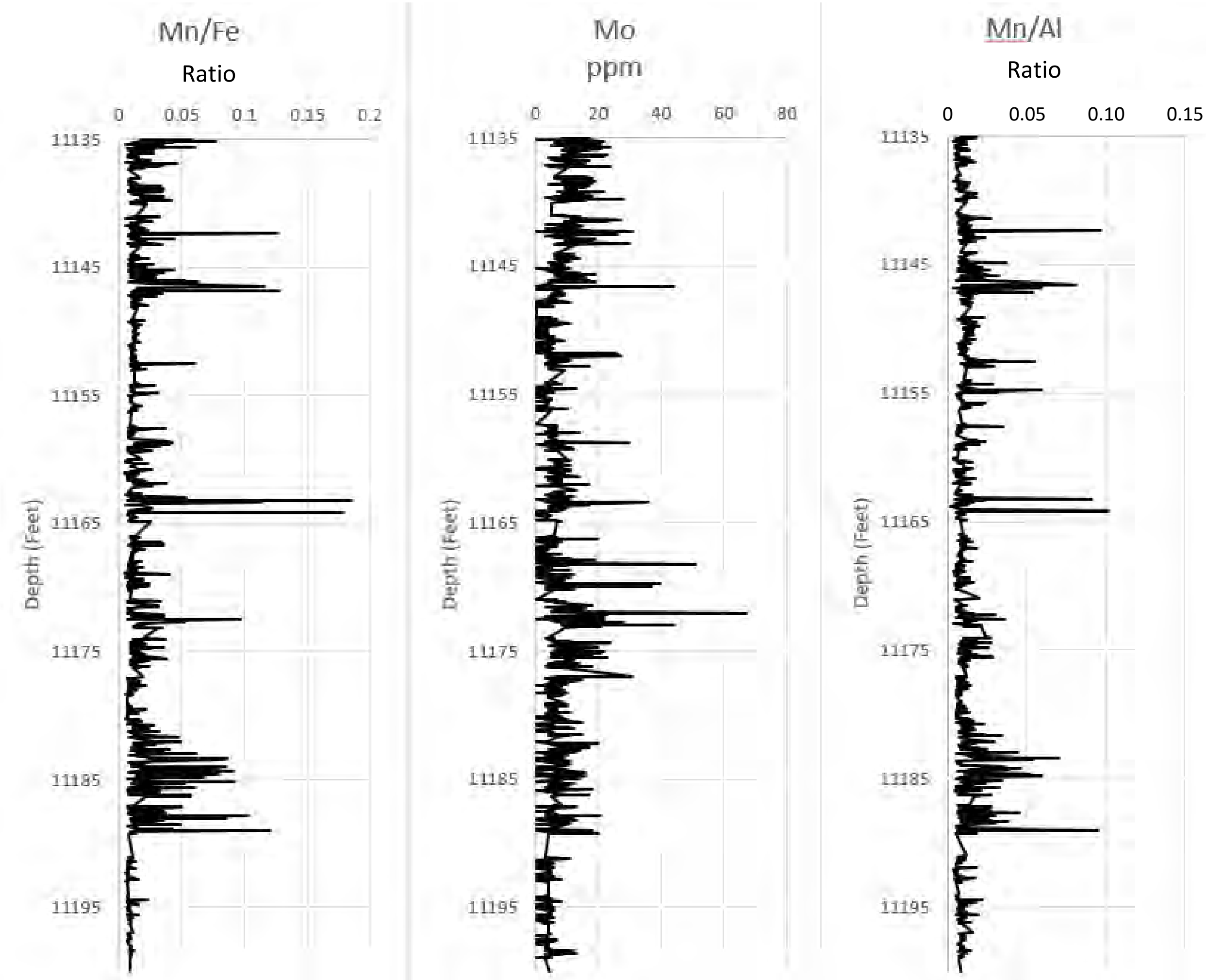


Figure 6*. Mo, Mn/Al, and Mn/Fr are all redox proxies. Redox proxies (Mo) indicate that siliceous shales were deposited in a relatively anoxic enviro Elevated Mo contents in organic-rich sediments are indicative of deposition from an anoxic and euxinic water-column, whereas the argillaceous shales were deposited in a relatively oxygenated environment.*

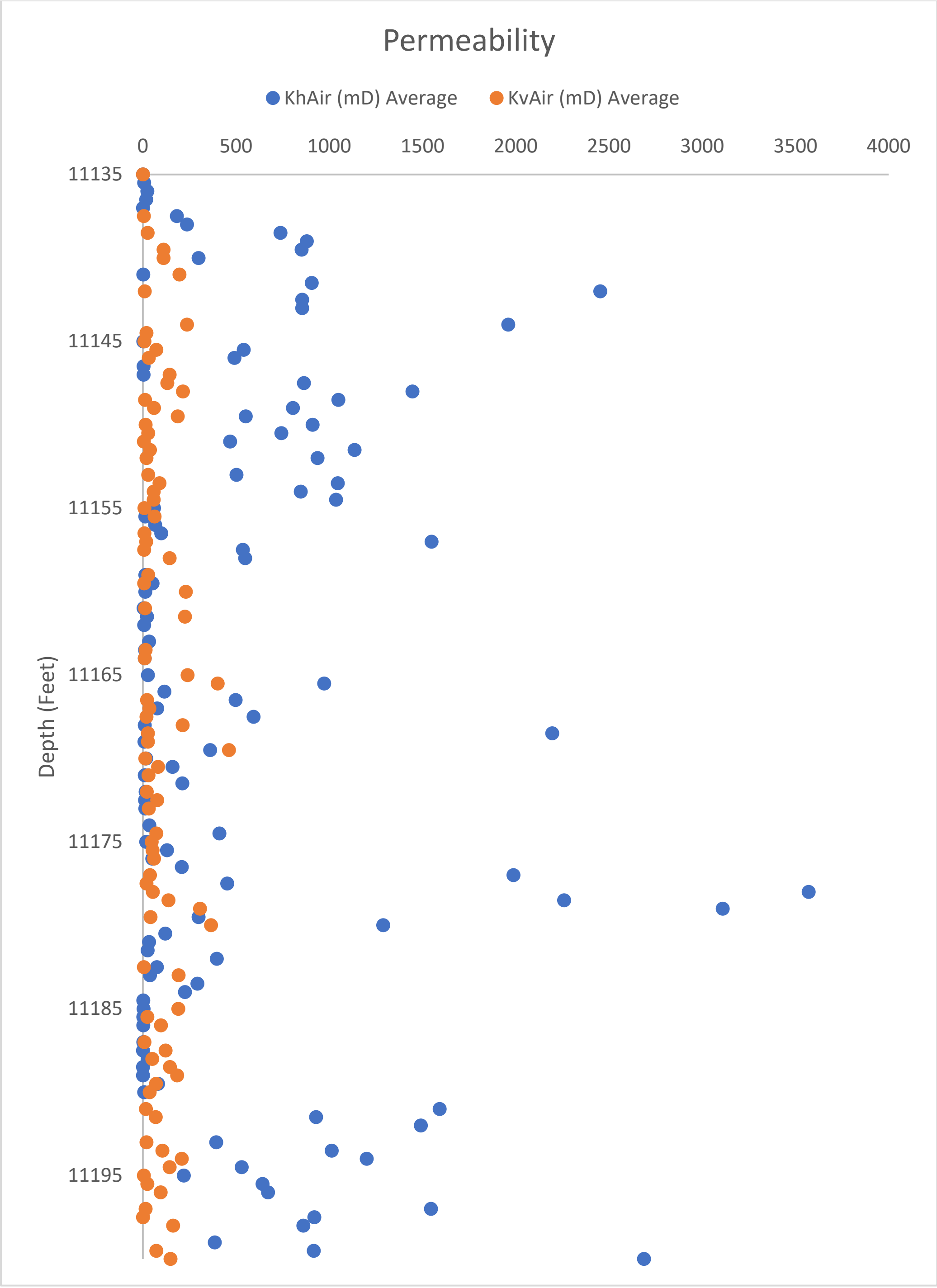


***Figure 7**. Permeability measurements of the Exxon #1 Smith core. Blue dots represent horizontal permeability (in mD), and orange points represent measured vertical permeability (in mD).*

Part 2 – KGS pXRF Research

Rogersville Shale Inorganic Geochemistry and Paleo-redox Proxies

David Harris, University of Kentucky – Kentucky Geological Survey

Bethany Royce and Phil Dinterman, West Virginia Geologic and Economic Survey

Abstract

Inorganic geochemistry of Rogersville Shale cores from five wells was determined by x-ray fluorescence spectroscopy (XRF). Data from commercial labs were contributed to the project for three recently drilled wells, and new XRF data was acquired for 2 wells by the Kentucky and West Virginia Geological Surveys. The resulting dataset was acquired from a mixture of instrument types (both wavelength and energy dispersive XRF), laboratories, and analytical methods. This introduces some uncertainty, and variability in the data was observed between wells analyzed by different labs and instruments. The data were suitable to analyze for paleoredox conditions present during Rogersville deposition using published elemental proxies for oxygenation levels. The goal of this task was to better understand controls on organic carbon distribution and preservation in the Rogersville.

Despite the analytical differences between wells and labs, the Rogersville XRF elemental data strongly suggest that deposition occurred under predominantly oxygenated conditions, resulting in low total organic carbon (TOC) for the majority of Rogersville mudstones. Redox proxies considered include degree of pyritization (DOP), and ratios of Ni/Co, V/Cr, U/Th. Most of these proxies indicated oxic to slightly dysoxic conditions during Rogersville deposition. This is consistent with facies interpretation of the cores, which indicates abundant bioturbation, thin siltstone/sandstone beds with current lamination, and cross-stratification, suggesting oxygenated conditions. Elemental enrichment factors for redox-sensitive elements (compared to average shales) were calculated and are generally low, again indicating oxidizing conditions. The Rogersville lacks laminated, non-bioturbated black shales typical of other higher TOC shales. Cored intervals in the Rogersville with TOC in the 1-3% range appear very similar to low TOC intervals. Controls on preservation of organic matter in the Rogersville remain elusive, since depositional environments are comparable between low TOC and higher TOC intervals.

Introduction

The inorganic geochemistry of mudstones is important not only to determine the bulk composition of these fine-grained reservoir rocks but also to characterize the depositional environment and oxygen conditions in which they were deposited (Jones and Manning, 1994; Algeo and Maynard, 2004; 2008; Rimmer, 2004; Rimmer and others, 2004). The oxygenation state of the depositional and shallow burial environment is a important control on the preservation of organic matter in sediments, in addition to sedimentation rate (dilution) and primary organic productivity (Tyson, 1995). The concentration of several trace metals in marine sediments is influenced by the reduction–oxidation state (redox) at the sediment-water interface and in shallow pore fluids (Algeo and Maynard, 2008). Several trace metals such as U, Ni, V, and Mo are more soluble in oxidizing conditions, and much less so in reducing conditions, becoming enriched in sediments under anoxic conditions that are also conducive to organic matter preservation (Tribovillard and others, 2006). Reviews and case studies of the use of trace metals in paleoredox analyses can be found in Algeo and Maynard (2008) Tribovillard and others (2006), and Jones and Manning (1994).

Many of these trace element proxies were developed with data from modern environments or Devonian and younger rocks. Paleoredox studies of Cambrian shales are less common, but the techniques and trace element behavior remain valid in these older shales. A good example is recent trace element and isotope research on the organic-rich Cambrian Alum Shale of Scandinavia (Gill and others, 2021).

Study Area and Data Distribution

Major and trace element concentrations derived from x-ray fluorescence (XRF) analysis were contributed to the project by industry partners from 3 wells, and new data were acquired from core from two wells. Figure 1 shows the location of the 5 wells with elemental data. The XRF data were limited to the Rogersville Shale, with slightly different stratigraphic distributions depending on the well. The well locations and stratigraphic distribution cover the main Rogersville Shale play area.

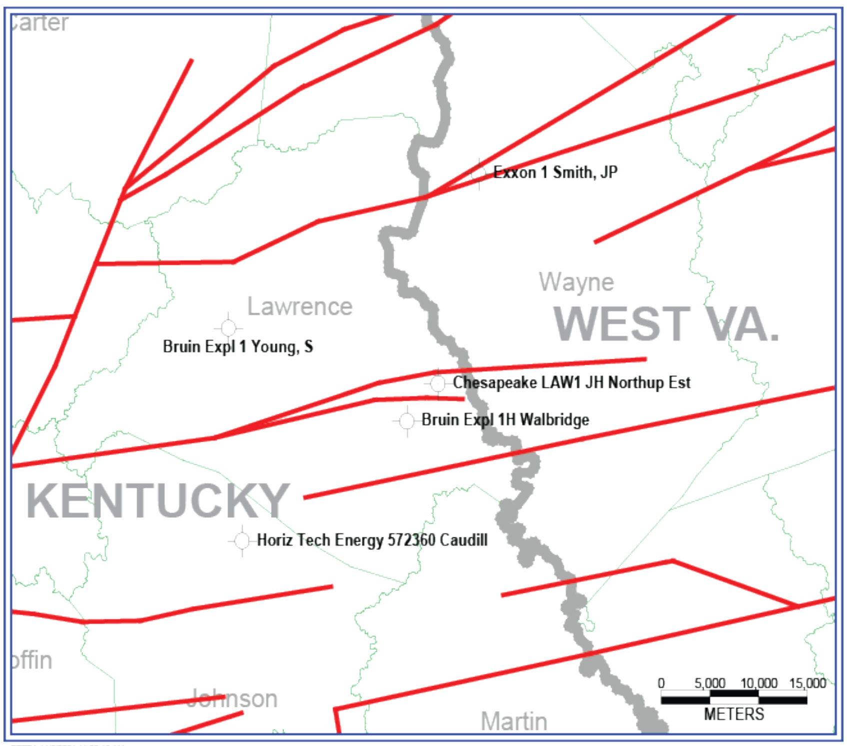


Figure 1. *Location map showing distribution of wells with x-ray fluorescence data. Data for the Exxon #1 Smith core and the Chesapeake LAW1 Northup wells were acquired in this study. Data for the other wells was contributed by industry partners.*

Data and Methods

X-ray fluorescence data acquired and compiled in this task varies by the type of instrument used and laboratory. Two primary types of x-ray fluorescence spectrometers are used to analyze samples for major and trace elements: wavelength dispersive XRF and energy dispersive XRF. Wavelength dispersive instruments (WD-XRF) measure x-ray energy by their wavelengths after diffraction through a crystal. These instruments are commonly more precise and have lower detection limits but are a bench-top non-portable design. Energy dispersive XRF (ED-XRF) instruments directly measure the energy spectrum of x-rays emitted from a sample. This technique is much faster than WDXRF, and in recent years several different portable hand-held XRF instruments have been developed to provide rapid ED-XRF analyses. The type of instrument used to acquire XRF data can affect the accuracy of the results, and this type of inter-laboratory variability has been seen in this study. Ideally all data should be acquired with the same instrument and analytical methodology to eliminate instrument variability. This was not possible in this study, and the various analytical methods are discussed below for each well.

Table 1 shows the various instruments and labs used to acquire the data. The only samples analyzed by WD-XRF were from the Horizontal Technology (EQT) Caudill well in Johnson County. The two Bruin Exploration wells did not have whole core, so a more limited number of sidewall core samples were analyzed at commercial labs by ED-XRF. Only major element data was available for the Bruin Exploration Young well. Two different labs were used to analyze sidewall cores from the Bruin Exploration Walbridge well using ED-XRF (assumed to be portable XRF instruments). The data from these labs differs significantly and is discussed in more detail below.

Table 1. List of XRF data sources and analytical instruments used for Rogersville Shale samples.

API	Well Name	County, State	Analyses	Lab	Instrument
1611502147	Horizontal Technology #572360 Caudill	Johnson Co., KY	190	Weatherford	WD-XRF
1612703100	Bruin Expl. #1 Young	Lawrence Co., KY	33	Ingrain	ED-XRF (majors only)
1612703200	Bruin Expl. #1 Walbridge Heirs	Lawrence Co., KY	18	Chemostrat	ED-XRF
			43	Ingrain	ED-XRF
1612703198	Chesapeake #LAW1 Northup	Lawrence Co., KY	209	Ky. Geol. Survey	ED-XRF (Bruker Tracer 4-SD)
4709901572	Exxon #1 Smith	Wayne Co., WV	1357	W.Va. Geol. Survey	ED-XRF (Bruker Tracer 5)

New data acquired as part of this study were from the Exxon #1 Smith and Chesapeake #LAW1 Northup cores by the West Virginia Geological Survey and the Kentucky Geological Survey, respectively. These datasets were acquired with different Bruker portable XRF instruments (ED-XRF). The Exxon Smith core was analyzed with a Bruker Tracer 5 instrument, while the Chesapeake Northup core was analyzed with an older Bruker Tracer 4-SD instrument. The detection limits and accuracy of the Tracer 5 instrument are thought to be improved over the Tracer 4-SD, but direct analytical comparisons were not made.

Discussion of specific well datasets follows.

Horizontal Technology #572360 Caudill, Johnson County, KY

This dataset was contributed by EQT and data quality for this well appears to be very good. The samples were taken from whole core, ground and homogenized, and analyzed on a WD-XRF instrument at Weatherford Labs. The main problem with this well is the lack of total organic carbon (TOC) content for the same samples with XRF data. This prevents cross-plotting TOC with other trace elements to look for covariance. Also, the main higher TOC (pay) zone in the Rogersville was not cored in this well. The core barrel jammed and no core was cut over this interval. Thus there is only XRF data for a few sidewall cores that have lower TOC values.

Bruin Exploration #1 Young, Lawrence County, KY

This dataset was contributed by Cimarex Energy, parent company of Bruin Exploration. The samples were sidewall cores and analyses used an ED-XRF, probably a portable instrument at Ingrain, Inc. (since acquired by Halliburton). Only major elements were analyzed for these samples, limiting analysis of the data that requires trace element data.

Bruin Exploration #1 Walbridge Heirs, Lawrence County, KY

This dataset was also contributed by Cimarex Energy. Two sets of XRF data were contributed from different labs (Ingrain and Chemostrat). Some of the sample depths are identical, but a few are unique to one lab or the other. Both datasets were acquired with a portable ED-XRF instrument. These datasets show significant differences in several major and trace element concentrations. Some examples of average element variability between the labs are shown below:

Element (ave.)	**Chemostrat Lab (n=18)**	**Ingrain Lab (n=43)**
Lead	10.5 ppm	429.3 ppm
Barium	897.8 ppm	1503.7 ppm
Silicon	18.7%	12.6%
Aluminum	7.5%	4.0%
Vanadium	64.5 ppm	26.9 ppm
Nickel	22.5 ppm	44.6 ppm

The largest variability is seen in lead and barium which are not important redox proxy elements. High barium could be contamination from drilling fluid, but the reason for high lead values in the Ingrain analyses is not known. Average lead in all other Rogersville cores ranges from 10-15 ppm. Silicon and aluminum, which occur primarily in detrital minerals also show some variation. Average vanadium and nickel vary by a factor of 2+ between the labs and are important redox elements. Because of this inter-lab variability data from the two labs were kept separate in subsequent data analyses.

Chesapeake #LAW1 Northup, Lawrence County, KY

Almost the entire Rogersville Shale was cored in the Chesapeake #LAW1 Northup well. Since no XRF data was provided to KGS by Chesapeake KGS acquired new data from this core. This core is at the Kentucky Geological Survey, where ED-XRF analyses were made on the thinner slabbed section of the core. Chesapeake contributed TOC data for all the samples from this core, and those sample locations were still marked on the core in chalk. Trace and major element data were acquired on the slabbed core face within the 2-3 inch sample depth intervals previously marked for TOC analysis. Thus, the XRF data is from within 1-3 inches of the TOC sample depth, but they are not from the exact same sample or a split. Care was taken to avoid analyzing siltstone laminations and carbonate beds to better characterize the organic-rich shale parts of the Rogersville.

208 core locations were analyzed from 11749.6 to 12,023.78 ft. at the bottom of the core. This sample range was centered on the higher TOC interval in the core from 11,868 to 11,961 ft. to allow identification of any trace element covariation with TOC.

A Bruker Tracer 4-SD portable XRF was used at the Kentucky Geological Survey's Earth Analysis Research Library to analyze the Chesapeake core. This instrument was adjusted by Bruker prior to this work to correct for drift of the detector due to its age. This instrument requires separate analyses for major and trace elements under different instrument condition. Spectrums for both major and trace elements were acquired and quantified using Bruker's mud rock calibration. This instrument and software does not calculate error factors for the analyses. Analytical conditions for the Tracer 4-SD were as follows.

	Major elements	**Trace elements**
Detector	Vacuum	Atmosphere
Filter	None	Filter 1: Ti 25u, Al 300u
X-ray tube voltage	15kV	40kV
Filament current	41ua	35ua
Scan time:	60 seconds	60 seconds

The instrument was checked at the beginning and end of each day with the SARM-41 carbonaceous shale standard.

When quantifying the XRF spectra using the Bruker mudrock coefficients some trace elements showed negative values. These values were assumed to be below detection limits for the instrument and were removed from the dataset.

Exxon #1 Smith

This 65 ft. slabbed whole core of the Rogersville Shale from Wayne County, West Virginia was analyzed with a portable Bruker Tracer 5i ED-XRF instrument at the W. Va. Geological Survey. The core was analyzed in detail, with a maximum sample increment of 0.1 inch, and commonly a much smaller sample interval, resulting in a total of 1,358 analyses. Analyses included all lithologies in the core (shale, siltstone/sandstone). The dataset does not include lithologic information for the analyses, so mudstone analyses cannot be separated from the other lithologies. Analysis spots were marked on the core, so this could be done in the future.

Instrument conditions used the Bruker Mudrock Air Dual settings with a 90 second (major elements) and 180 second (trace element) scan times. The Tracer 5i calculates error values which are included in the XRF data file.

When reviewing the Exxon Smith major element data the average sulfur and calcium percentages were higher than the other wells studied. Higher calcium could be explained by inclusion of calcite-cemented siltstone/sandstone beds in the analyses. Sulfur however was significantly higher than any of the other wells and cannot be explained by lithologic variability in the samples:

	Exxon #1 Smith	**Average of other wells**
Calcium	10.4%	9.5%
Sulfur	3.6%	0.6%
Iron	2.7%	3.4%

Average iron in the Smith data is actually lower than the average for the other wells, so the higher sulfur cannot be attributed to pyrite.

The Smith core is the oldest core analyzed in the study (drilled in 1974) and Dr. Amy Weislogel at W. Va. University suggested the anomalous sulfur could be from post-coring precipitation of gypsum on the slabbed surface of the core. Several core samples from the Smith well were examined macroscopically at KGS, and on a SEM with energy-dispersive x-ray analysis capabilities. This confirmed the presence of gypsum on the surface of the core (Figure 2.) The SEM image shows platy crystals on the core surface that bridge fractures in the core caused by desiccation or unloading. The element maps for this view show these crystals contain sulfur and calcium, but no iron, eliminating pyrite as the source. XRF analyses from this interval at 11.200 ft. indicated around 8% sulfur, which reflects this surface contamination. The calcium and sulfur data from this core are regarded as anomalous, and this affects subsequent calculations of degree of pyritization (DOP), a useful redox indicator.

It is also difficult to compare the Exxon Smith XRF data to the available TOC for that core, but TOC has been matched to the closest corresponding depths in the XRF file.

Figure 2. *Scanning electron microscope images of core sample from 11,200 ft. in the Exxon #1 Smith well showing post-coring gypsum precipitate on the slabbed core surface. XRF analysis of this core footage measured around 8% sulfur.*

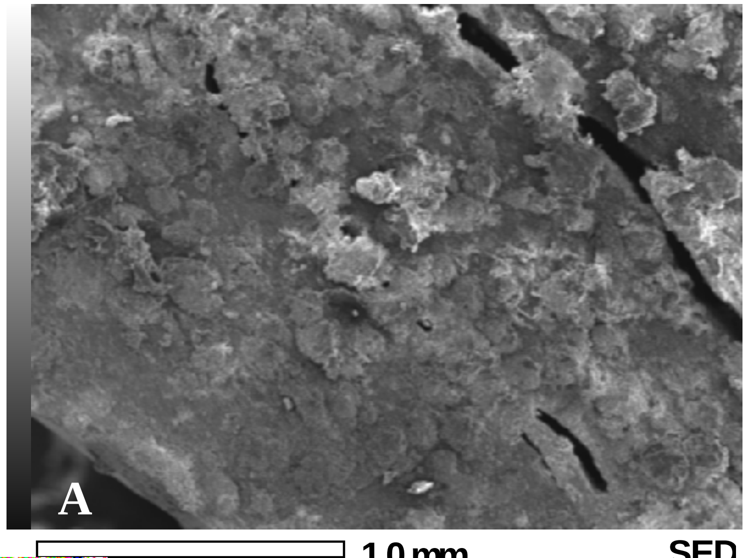
A. *secondary electron image of slabbed core surface. Precipitate is also present in and on open fractures induced by core desiccation and expansion.*

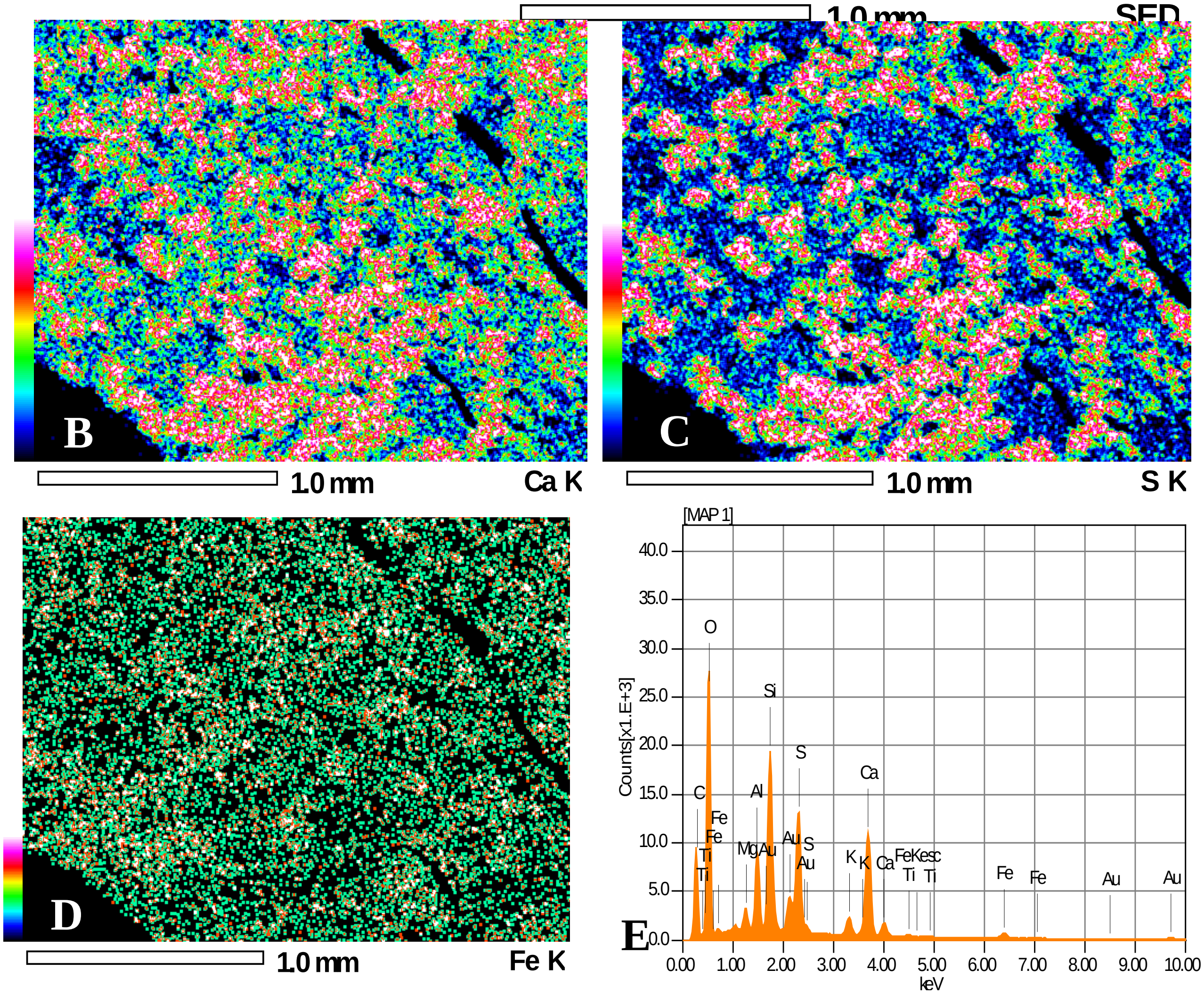
B. *element map for calcium. In all element maps warmer colors represent higher element concentrations.*

C. *element map for sulfur.*

D. *element map for iron which shows no correlation with sulfur map, ruling out pyrite as the sulfur source.*

E. *SEM-EDX spectrum for field of view in A.*





To summarize, we compiled or acquired new data for 5 Rogersville wells. The data were acquired at 5 different labs, with at least 4 different instruments likely under different operating conditions. Most of the data was collected with portable XRF instruments (ED-XRF), while one set (Horizontal Tech. Caudill) was collected with a wavelength dispersive laboratory bench instrument.

Known problems with the overall Rogersville XRF data include:

- The Ingrain labs data for the Bruin Walbridge well has anomalous high lead and barium concentrations. Chemostrat dataset for this well is preferred but has fewer samples.
- The Bruin Young dataset lacks trace elements which are most useful for redox interpretation.
- The Chesapeake Northup dataset was acquired with an older pXRF instrument (Tracer 4-SD) at KGS that is less accurate than the newer Tracer 5i used by the West Virginia Geological Survey. The mudrock calibrations were different for the 2 instruments. KGS has since purchased a Tracer 5 instrument and comparisons of the 2 instruments will be made soon.
- The Exxon Smith data acquired by the West Virginia Survey has high sulfur and calcium values for some samples, caused by post-coring gypsum precipitation on the core surface. This prevents the use of these data for degree of pyritization (DOP) calculations.
- The best dataset is from the Horizontal Tech. Caudill well, but this well did not core the primary pay zone and most of the data is for low-TOC, non-pay intervals.

Despite the potential for inter-lab variability and known issues noted above, interpretation was straightforward, and the XRF data has proven valuable in assessing the paleo-redox conditions present during Rogersville deposition.

Depositional Setting and Lithofacies

The focus of this study has been on the use of major and trace element data from Rogersville mudstones to help interpret the role of paleoredox conditions as a fundamental control on organic carbon content. Elevated total organic carbon (> 1 weight percent) occurs in a limited interval (~60 ft.), but laterally mappable horizon in the middle of the Rogersville. Continuous core across this higher TOC interval was available from the Chesapeake #LAW1 Northup well. Additional whole core was contributed from the Horizontal Technology #572360 Caudill well, but this well did not core the organic-rich pay zone. Detailed sedimentologic interpretation of this core was not a formal task in this study, but some observations are warranted to provide context for the geochemical data.

The Rogersville Shale in eastern Kentucky and West Virginia was deposited in an intrashelf basin that formed cratonward of a shelf-edge carbonate platform to the southeast in northern Tennessee and southwest Virginia (Read and Repetski, 2012). The alternating shale/carbonate formations of the Conasauga Group (in ascending order, the Pumpkin Valley Shale and Rutledge Ls., Rogersville Shale and Maryville Limestone, Nolichucky Shale and Maynardville Limestone) resulted from repeated transgressive/regressive cycles of carbonate shelf progradation *cratonward* to the northwest over deeper water intrashelf slope/basin shales (Rankey and others, 1994; Hasson and Haase, 1988). This intrashelf basin included the Rome Trough along its northwestern margin. The exposed cratonic clastic source area lay to the north with the Kerbel delta providing most of the siliciclastic sediments (reference).

Based on the 2 cores examined in this project Rogersville lithofacies are heterolithic marine sediments deposited in slope to basinal settings. They consist of thinly-bedded calcareous mudstones, siltstones and very-fine grained sandstones, and are commonly glauconitic. Lithofacies are defined primarily on the amount of mudstone interbedded with coarser clastics. Nodular limestone becomes more abundant in the Northup core in the upper Rogersville as it grades into the overlying Maryville Limestone. The Rogersville is characterized by thick lithofacies intervals that lack obvious cyclicity. Thin lenticular bedding, current lamination (hummocky and ripple cross lamination), and moderate levels of bioturbation throughout are the primary sedimentary structures. Lithofacies transitions are gradational. Based on preliminary work, three lithofacies have been recognized in the Rogersville:

Distal slope/basin mudstone

Heterolithic mudstone, siltstone and very-fine grained sandstone with mudstone greater than 50%. Thin lenticular bedding in millimeter to 5 cm. thick beds. Silt and sand beds have horizontal to low angle ripple to hummocky cross-bedding. Starved ripple and climbing ripple cross bedding common. Burrows and bioturbation are common throughout with *Planolites* and *Chondrites* most abundant. Sandstone beds typically have irregular, scoured basal contacts and more uniform upper contacts. Normal grading is present in some beds. Beds commonly pinch-out laterally within the core. Mudstone is typically dark gray and fissile. Bed dip is generally horizontal with inclined depositional dip on some bedding surfaces. Soft-sediment deformation present as low angle faults with small displacement, and minor slumps. 1-3 cm round to elongate limestone nodules are present in some intervals. These are fine-grained to pelletal and commonly are internally burrowed. Siltstones and sandstones are cemented by calcite and non-porous. Fossil grains include fragments of trilobites and thin brachiopods, commonly found as a lag at the base of sand/siltstone beds. This lithofacies is interpreted as a distal slope deposit, deposited below normal wave base. Silt and sandstone beds are interpreted as storm deposits.

Proximal slope sandstone/siltstone

Similar in many respects to the distal mudstone lithofacies, but siltstone/sandstone is greater than mudstone. Thin, lenticular siltstone and very-fine grained sandstone beds occur up to 5 cm. Ripple and hummocky cross bedding is more abundant. Burrowed throughout with *Planolites* and *Chondrites* the predominant trace fossils. Fine-grained limestone nodules occur in this lithofacies also. Flat pebble intraclast conglomerate beds are common, but thin (less than 10 cm.). This lithofacies is interpreted as a shallower slope deposit than the distal slope lithofacies. Wave energy is higher with coarser grain size and less mudstone deposited.

Nodular limestone

Thin-bedded nodular limestone occurs in the upper part of the Northup core. These limestones are mudstones to peloid packstones and occur in the upper part of a coarsening upward sequence. This lithofacies is interpreted as an upper slope deposit which developed with lower clastic influx.

In summary, sedimentary features in the Rogersville suggest deposition in oxic to disoxic environment below daily wave base, but above storm wave base. This is supported by the abundance of bioturbation, coarser siltstone/sandstone beds and laminations with evidence of current transport, and the dark gray color. Sedimentary features have not been useful in distinguishing low TOC shale from higher TOC shale, as seen in Figure 3.

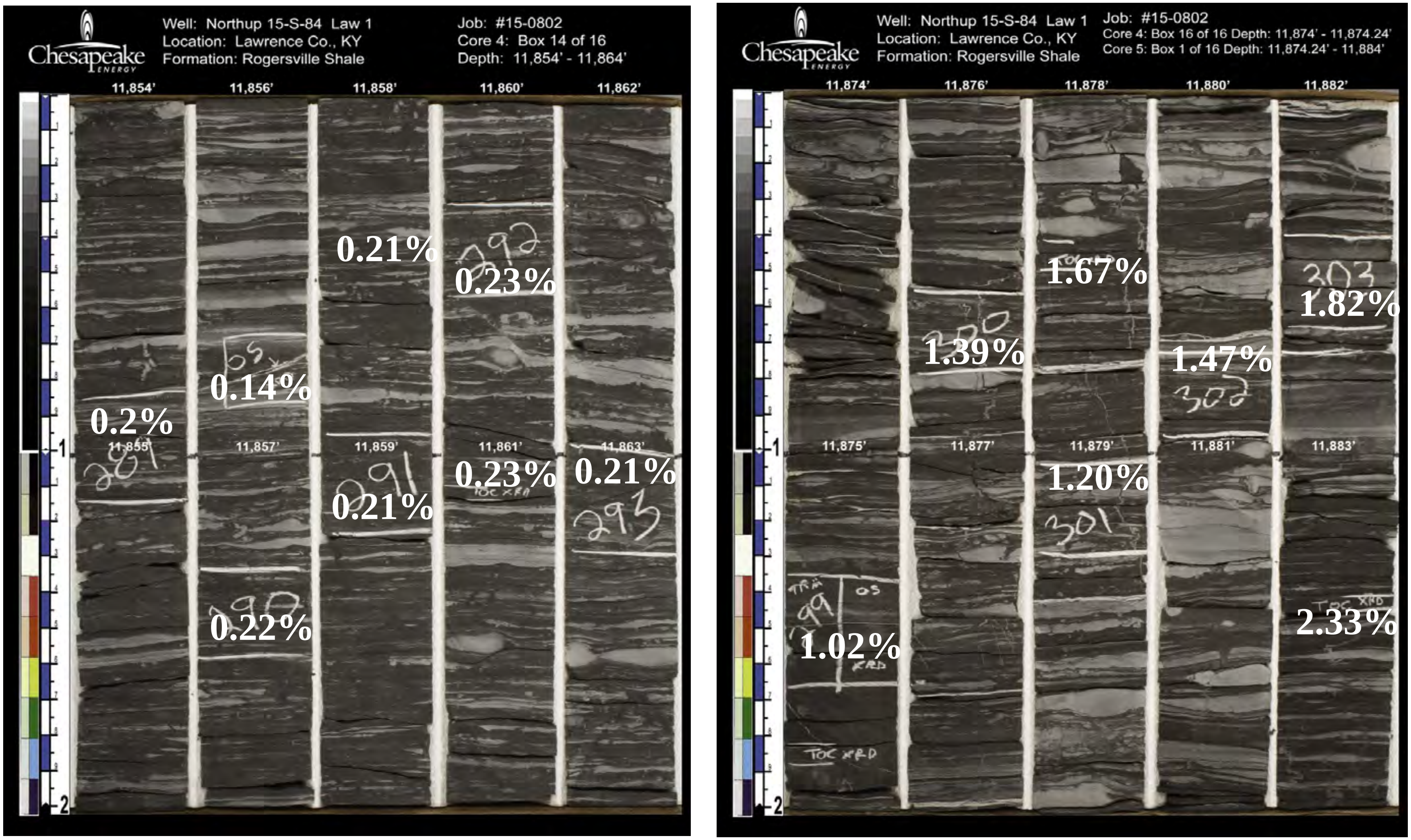


Figure 3. *Comparison of Rogersville core from the Chesapeake #LAW1 Northup well. These 2 boxes are 20 feet apart and have very similar color, sedimentary structures and bioturbation, but differ significantly in organic carbon content. TOC weight percent is marked at sample depths The box on the right is in the higher TOC pay zone.*

Major and Trace Element Paleoredox Proxies

Depositional facies does not directly predict organic carbon content in the Rogersville. Intervals with very similar lithology and sedimentary structures have very different TOC contents. To determine controls on organic richness in the Rogersville inorganic geochemical data from x-ray fluorescence was compiled and new XRF data acquired on two cores. These data have been used to interpret the paleoredox conditions during Rogersville deposition.

Major and trace element data has been interpreted using some of the more commonly used published redox indicators. This is a large field of study with an extensive literature, so this discussion is based on indicators most commonly applied. Jones and Manning (1994) evaluated numerous trace element indices and tested them on Jurassic mudstones from the North Sea. They utilized factor analyses to identify which elements or ratios were reliable indicators of paleo-oxygenation conditions. They found the following 4 indices to be reliable indicators of oxic, dysoxic, and anoxic conditions:

- Degree of pyritization (DOP)
- U/Th
- V/Cr
- Ni/Co

In addition, various researchers have used trace element enrichment factors above average shales as redox indicators (Algeo and Maynard, 2004; Rimmer, 2004). These indices and enrichment factors are discussed and presented below.

Degree of Pyritization

Raiswell and others (1988) defined a proxy for bottom-water oxygenation based on the ratio of pyritic iron to the sum of pyritic iron and acid-soluble iron, calling it degree of pyritization (DOP). DOP has been used in many other studies as an paleo-oxygenation indicator (Jones and Manning, 1994; Hatch and Leventhal, 1992; Rimmer, 2004; Lyons and Severmann, 2006).

DOP is defined the ratio pyritic Fe/(pyritic Fe + HCl-soluble Fe) (Raiswell and other, 1988). This ratio reflects the proportion of iron in pyrite to total iron. In oxidizing environments pyrite is formed only in the sediments due to microbial sulfate-reduction creating H_2S that reacts with detrital iron minerals to form pyrite. (Raiswell and others, 1988). Under oxidizing conditions oxygen is supplied to the sediment by bioturbation, resulting in loss of pyrite from oxidation, and low pyritic iron values. In anoxic and euxinic environments sulfate reduction allows more detrital iron to be converted pyrite and it is not subject to oxidation. Thus high values of this ratio indicate anoxic or euxinic conditions, and low values indicate oxidizing environments. Raiswell and others (1988) used several different shale formations to empirically calibrate DOP to the oxygenation level based on sedimentology and fauna indicators of oxygenation. They proposed the following DOP values as indicators for the following oxygenation levels:

DOP < 0.42	Oxic
0.42 < DOP < 0.75	Dysoxic
0.75 < DOP < 1.0	Anoxic and euxinic

In this study, DOP was calculated following the method of Rimmer (2004), who calculated DOP_{total} using total iron rather than pyritic Fe+HCl-soluble iron:

$$DOP_T = \text{pyritic Fe/total Fe}$$

Pyritic iron was calculated from total sulfur data assuming all sulfur occurs as pyrite. If all sulfur occurs as pyrite, by using pyrite stoichiometry: pyritic Fe % = total S % * 0.871

Raiswell and others (1988) mention a few constraints on the use of DOP to characterize paleoenvironments:

1) Some organic carbon must be present to allow sulfate reduction and pyrite formation to occur or else non-pyritic sulfur may be present. DOP is not reliable in low-TOC rocks such as sandstones. All of the Rogersville samples had greater than 0.1% TOC, and most had greater than 0.15% as recommended by Raiswell and other (1988).
2) Sediments older than Devonian should not be used due to the presence of more reactive organic carbon in pre-Devonian shales (lack of terrestrial plant-derived organic matter). More reactive organic matter could result in increased pyrite precipitation and higher DOP values in oxic and dysoxic environments. As the data indicate below, the Rogersville DOP data is consistently very low, and falls well within the oxic DOP range. So there is no ambiguity from possible higher DOP ranges in these Cambrian shales. If the DOP values are elevated due to the pre-Devonian age, it does not affect the interpretation.

DOP was calculated for 4 of the 5 wells with XRF data. DOP ratios were invalid for the Exxon #1 Smith core data because of anomalous high sulfur from post-coring gypsum precipitation. Calculating DOP for the Smith core was the first indication that there was a problem with the data, as many DOP values were greater than 1 due to excessive non-pyritic sulfur.

DOP values for the other 4 wells are consistently low, and all fall in the oxic field as defined by Raiswell and others, (1988). DOP data for the Northup, Caudill, and Young wells are plotted as histograms in Figure 4. The DOP data for the Bruin #1 Walbridge well is shown with the two labs plotted separately on a bar chart.

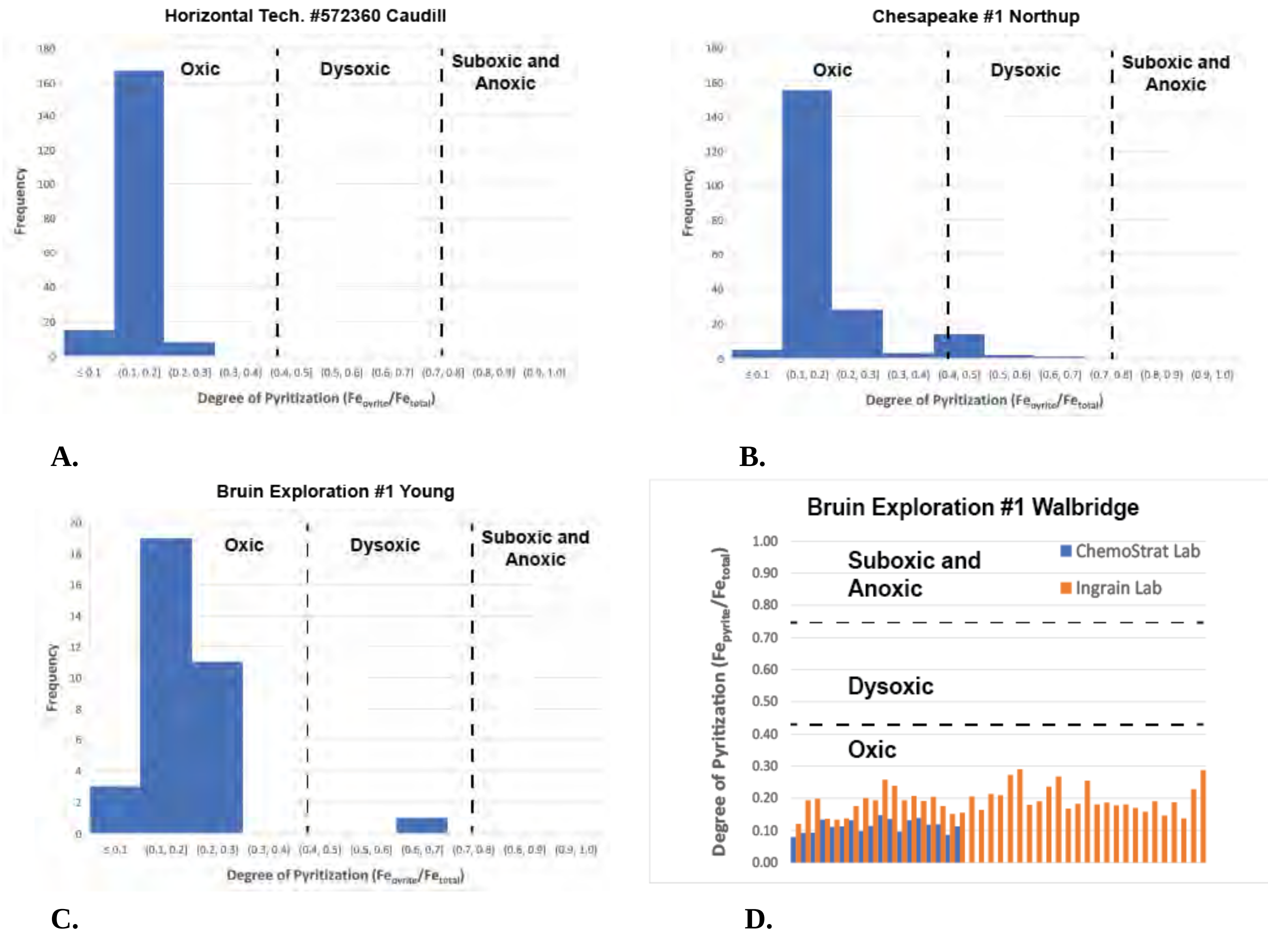


Figure 4. *Histograms showing distribution of degree of pyritization (DOP) ratios for Rogersville cores. Ranges for redox environments are from Jones and Manning (1994). All cores show strongly oxic conditions during deposition based on this proxy. A. Horizontal Technology Caudill. B. Chesapeake Northup. C. Bruin Young. D. Bar chart for Bruin Walbridge well. Data from different labs are plotted as separate series, and illustrates inter-lab variability in the XRF data. Both labs indicate oxic conditions during Rogersville deposition.*

V/Cr

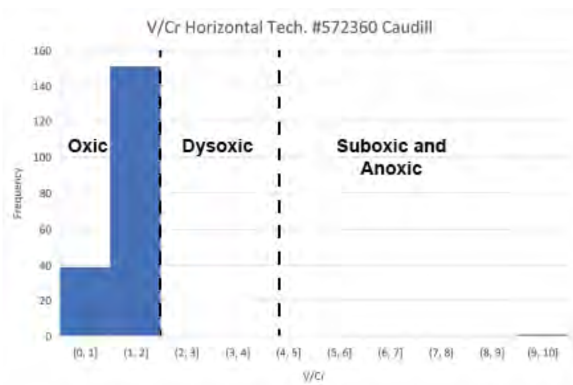
The ratio of the trace element vanadium normalized to chromium has been proposed as a redox indicator (Jones and Manning, 1994 and references cited therein). Vanadium is commonly bound to organic matter under reducing conditions, while chromium is part of the detrital clastic fraction, typically located in clays. Higher values of this ratio indicate more reducing conditions. Jones and Manning (1994) cite the following environmental ranges for V/Cr based on previous work:

$V/Cr < 2.0$	Oxic
$2.0 < V/Cr < 4.25$	Dysoxic
$V/Cr > 4.25$	Suboxic and anoxic

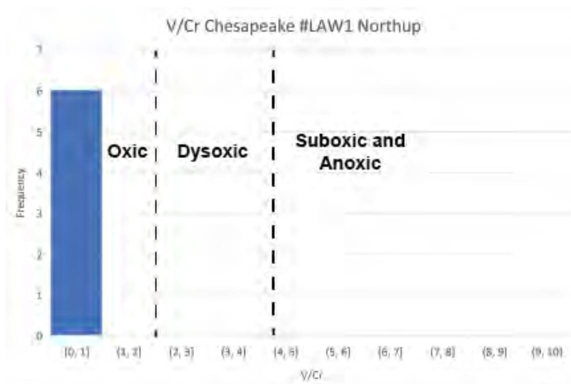
V/Cr values were calculated for 4 of the 5 study wells (trace element data was not available for the Bruin #1 Young well) and are shown in Figure 5. Several issues were encountered with measuring vanadium and chromium that affect this ratio. The most consistent vanadium and chromium data appear to be in the Exxon Smith and Horizontal Technology Caudill wells. For the Bruin Walbridge wells average V and Cr data from the two different labs differ by a factor of about 2, and V/Cr ratios are significantly different for the 2 labs.

In the Chesapeake Northup core, analyzed at KGS with an older Bruker Tracer 4 instrument, most of the V values were below detection limits. Cr data was better, with valid data measured, but this ratio could only be calculated for 6 samples. The newer Tracer 5 instrument used by the West Virginia Geological Survey for the Exxon Smith core was better able to measure vanadium and chromium, but still had numerous samples below detection limits.

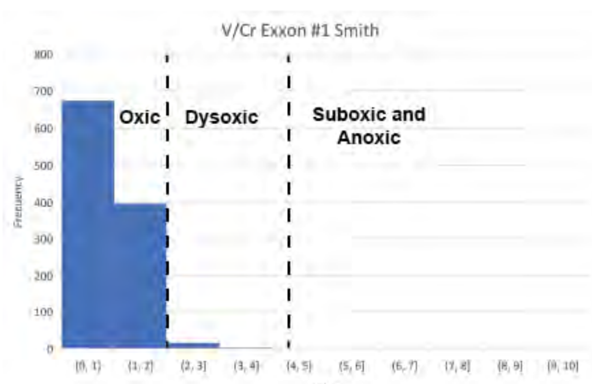
Almost all of the V/Cr ratios are below 2.0 indicating oxic depositional conditions. The only exceptions are except a few of the Chemostrat Labs samples in the Bruin Walbridge and a few of the Exxon Smith samples.



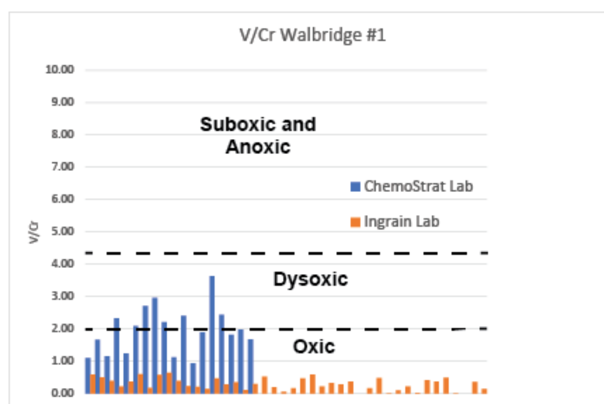
A.



B.



B.



D.

Figure 5. *Histograms for the ratio V/Cr, a proxy useful in interpretation of paleoredox conditions. Ranges for oxic, dysoxic, and suboxic/anoxic environments are from Jones and Manning (1994). A. Horizontal Technology Caudill core; B. Chesapeake Northup core, Note that due to detection limits for vanadium on the KGS instrument only 6 data points are plotted from this core. C. Exxon Smith core, D. bar chart showing data from 2 different labs for the Bruin Walbridge well showing significant differences between the V/Cr ratios.*

Ni/Co

Like V/Cr, the ratio of nickel to cobalt (N/Co) has been used as a redox indicator (Jones and Manning, 1994 and references therein). Higher values indicate reducing conditions. Cobalt is thought to reside primarily in the detrital sediment fraction, but can be incorporated into authigenic iron sulfides in anoxic conditions (Algeo and Maynard, 2004). By calibrating to DOP values, Jones and Manning (1994) propose the following environmental ranges for Ni/Co ratios.

Ni/Co < 5.0	Oxic
5.0 < Ni/Co < 7.0	Dysoxic
Ni/Co > 7.0	Suboxic and anoxic

Ni/Co was calculated for 4 wells (no trace element data for the Bruin Young well). The distribution of values is shown in Figure 6 with environmental ranges from Jones and Manning (1994).The majority of Ni/Co values are below 5.0 indicating oxidizing conditions. The Exxon Smith core had a few Ni/Co values between 5 and 6. The Bruin Walbridge data differs by lab as observed with other proxies. The Walbridge Chemostrat Ni/Co data is all below 3.0, and the Ingrain data is higher, mostly less than 4.o, with a few samples between 5 and 7.

The Horizontal Technology Caudill well has a much broader range of Ni/Co values, with most samples in the 1-3 range, but more values above 5 and some as high as 11.6. TOC data was not available for these higher Ni/Co ratio samples. Finally, the Chesapeake Northup core is dominated by Ni/Co values below 3.0, with 3 values between 5 and 9.6. These high values may be anomalous because TOC values for all of those were very low (<0.22%).

Ni/Co ratios vary by well, but most fall in the oxic range (<5.0) as proposed by Jones and Manning (1994).

U/Th

The uranium to thorium ratio is another redox proxy that Jones and Manning (1994) showed to be a reliable indicator. Other studies have shown positive covariation of uranium with TOC and enrichment with increasing reducing conditions (Algeo and Maynard, 2004; Tribovillard and others, 2006). Thorium is associated with the detrital fraction of sediments, commonly in clay minerals. It is immobile in low temperature environments (Jones and Manning, 1994). Uranium is soluble in higher valence states, but is fixed under reducing conditions. Higher U/Th ratios indicate reducing conditions and often correlates to higher TOC.

Oxygenation ranges for U/Th proposed by Jones and Manning (1994) are:

U/Th < 0.75	Oxic
0.75 < U/Th < 1.25	Dysoxic
U/Th > 1.25	Suboxic and anoxic

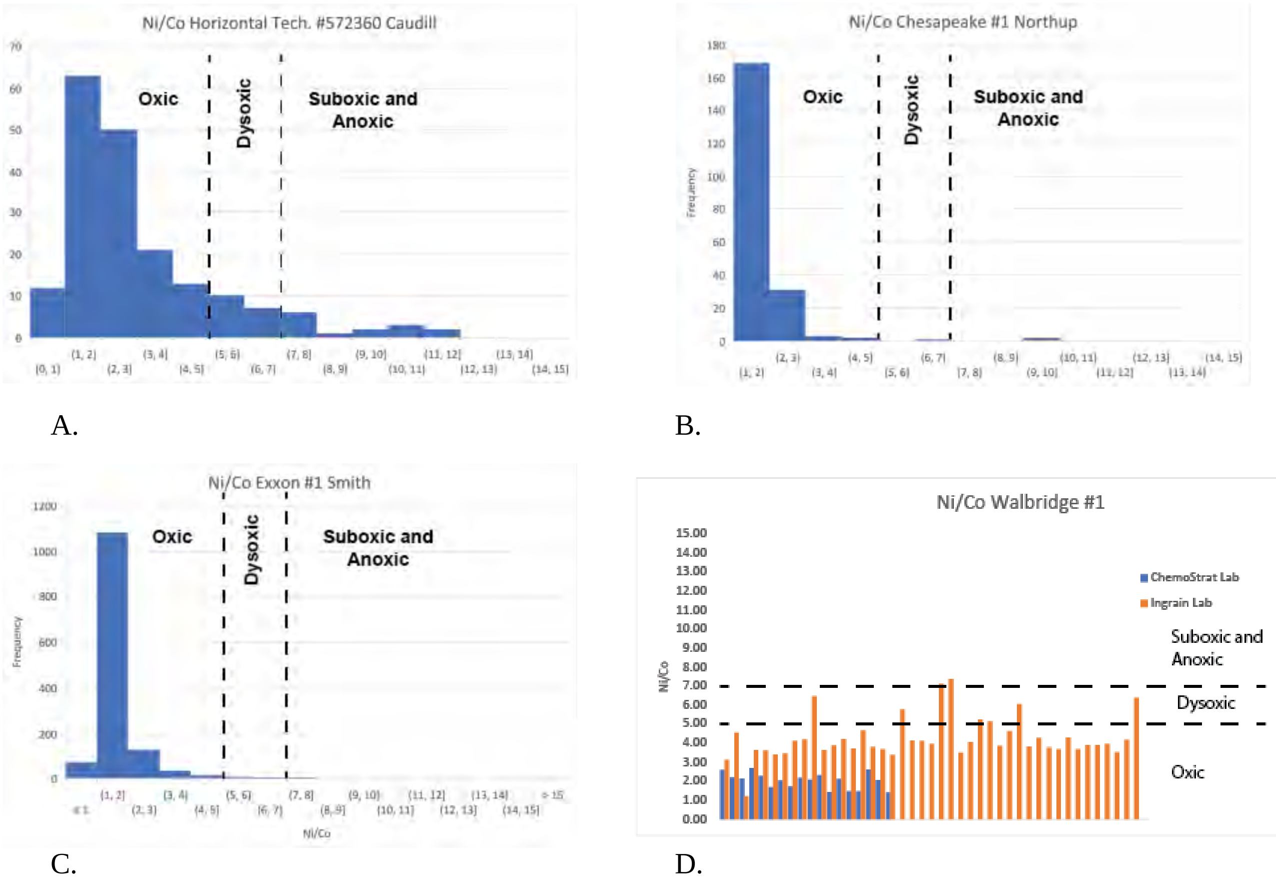
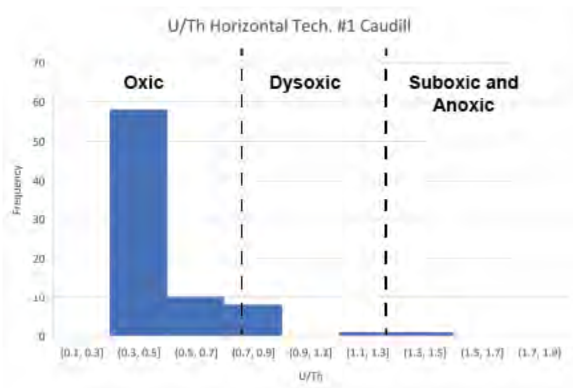


Figure 6. *Histograms showing distribution of Ni/Co ratios, with environmental ranges from Jones and Manning 1994). A. Horizontal Technology Caudill core; B. Chesapeake Northup core; C. Exxon Smith core, and D. bar chart for the Bruin Walbridge well with 2 data series for labs used in this well. Note significant difference between the labs, even though both indicate strongly oxidizing conditions during Rogersville deposition.*

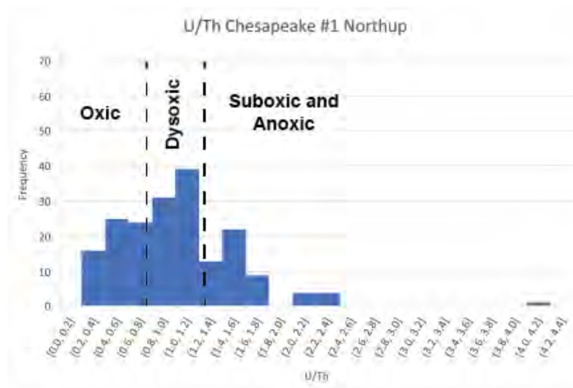
Uranium (and thorium) are very low in the Rogersville with average U concentrations ranging from 1ppm (Bruin Young well) to 10ppm (Chesapeake Northup well) (Table 2). Uranium values are much higher in the Northup core than the other wells. This may be caused by analytical variability with the older Bruker Tracer 4 instrument. The Exxon Smith core averaged about 5ppm using the newer Bruker Tracer 5 instrument. However the Exxon Smith core has the lowest thorium concentrations of the 5 wells, averaging 1.5ppm compared to 7-10ppm in the other wells.

Plots of U/Th are shown in Figure 7. These histograms show the distribution of U/Th values compared to the environmental ranges proposed by Jones and Manning (1994). These plots show the most variability between wells of all the redox indicators. This may be due to the very low concentrations of uranium approaching the detection limits of the handheld XRF instruments. The Horizontal Technology Caudill data, run on a laboratory WD-XRF, shows a strong oxic signal. The Chesapeake Northup and Exxon Smith data indicate more dysoxic and anoxic conditions. The Exxon Smith data shows the most reducing conditions, but also has the lowest thorium values, which would increase the ratio. The Bruin Walbridge and Young data indicate predominantly oxic conditions.

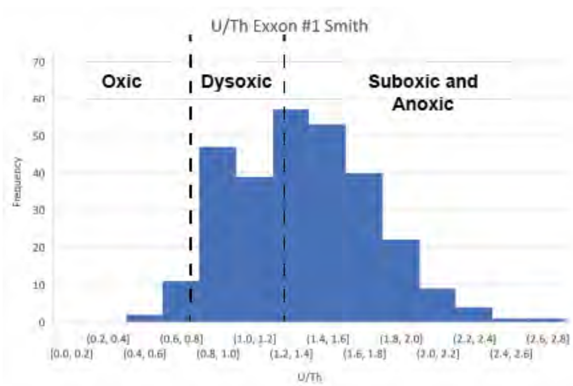
Due to the variability in uranium and thorium measured in these wells, the U/Th ratio may not be a reliable redox indicator in the Rogersville. Due to low concentrations of both U and Th, better data may be required to use this proxy with confidence.



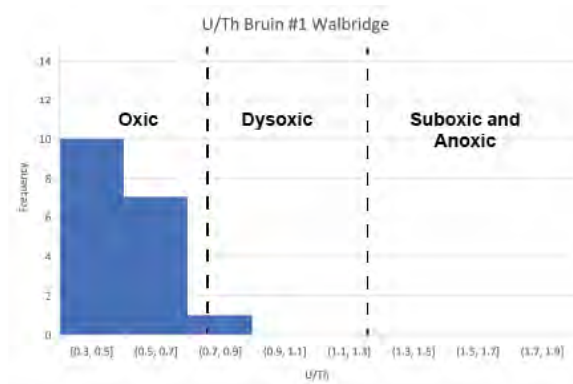
A.



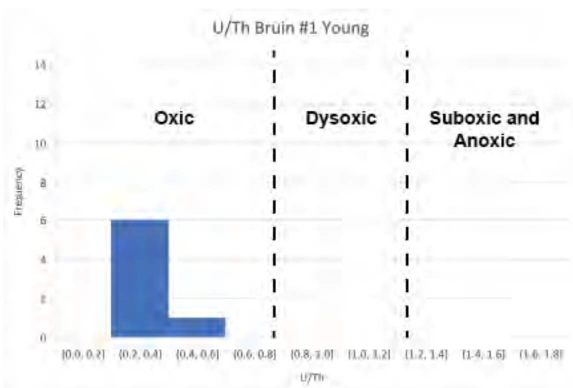
B.



B.



D.



E.

Figure 7. *Histograms showing distribution of U/Th ratios with environmental ranges from Jones and Manning 1994. Data shows inconsistent results possibly due to very low U and Th concentrations in the Rogersville. A. Horizontal Technology Caudill. B. Chesapeake Northup. B. Exxon Smith. D. Bruin Walbridge (Chemostrat dataset, n=18). E. Bruin Young (n=7).*

Table 2. *Rogersville Shale average redox indices and enrichment factors for key redox sensitive elements compared to average shale concentrations from Wedepohl (1971). The Bruin Walbridge well had data from 2 labs: top row is from Chemostrat and bottom row is from Ingrain. DOP is degree of pyritization, and is anomalous for the Exxon Smith due to excess sulfur from post-coring gypsum on core surface.*

	Average Redox Indices				Enrichment Factors (EF) Compared to Average Shale							
Well Name	**Ni/Co**	**V/Cr**	**U/Th**	**DOP**	**Co EF**	**Cr EF**	**Cu EF**	**Mo EF**	**Ni EF**	**Pb EF**	**V EF**	**Zn EF**
Horizontal Technology #572360 Caudill	3.23	1.19	0.29	0.14	1.48	0.89	0.65	0.22	0.90	0.97	0.73	0.99
Bruin #1 Sylvia Young			0.13	0.19								
Bruin #1 Walbridge Heirs	2.02	1.96	0.50	0.11	0.67	0.47	0.74	1.74	0.37	0.62	0.58	1.00
	4.24	0.32		0.19	1.29	2.13	1.77	0.40	1.47	**49.20****	0.46	2.07
Chesapeake Northup	2.02	0.17	1.05	0.19	1.20	0.65	0.69	3.53	0.79	0.80	0.93	1.01
Exxon #1 Smith	1.71	0.84	1.40	**1.2***	2.45	1.16	1.13	7.33	1.06	2.03	0.78	1.62

* DOP not valid due to unreliable sulfur data (cannot be > 1)

** Pb EF suspect due to high elemental Pb values in this well

Enrichment Factors

Redox sensitive trace elements are typically enriched in sediments in reducing environments. Enrichment factors over average shale composition for the trace elements Co, Cr, Cu, Mo, Ni, Pb, V, and Zn were calculated following the method of Rimmer (2004). This involved normalizing the element concentration to aluminum which represents the detrital contribution, and dividing the element in question by the same Al-normalized element in an average shale:

Enrichment factor = element/Al / element/Alaverage shale

Average shale data used was from Wedepohl (1971). Average enrichment factors for the various wells are included in Table 2. Most trace elements show very little enrichment or are less enriched than average shales. The obvious anomaly is Pb enrichment in the second Walbridge dataset due bad Pb values in those analyses.

Molybdenum shows moderate enrichment in two wells, the Chesapeake Northup (3.5) and Exxon Smith (7.3). Mo data from the Northup well was very close to the limit of detection with many samples below detection limit. The number of valid samples is limited, with a couple of anomalous 85ppm values that could be errors. This well was analyzed with the older Bruker Tracer 4 instrument.

The Exxon Smith data shows higher Mo values and was analyzed with a more sensitive Bruker Tracer 5 instrument. It still shows the highest Mo enrichment of any of the wells studied. Future work will include re-analysis of the Chesapeake Northup core with a similar Tracer 5 instrument to try and replicate those results.

Conclusions

Major and trace element data for five Rogersville Shale wells was compiled and/or acquired to aid in understanding controls on organic carbon distribution in the formation. Various issues with data acquisition and methodology present challenges in comparing data from different wells directly. Overall environmental proxies using redox-sensitive trace elements indicate oxidizing conditions prevailed during Rogersville deposition, and account for the low total organic carbon observed in the majority of the Rogersville. Paleoredox proxies within higher TOC intervals (1-3%TOC) indicate oxidizing conditions, so the fundamental control on organic preservation in the Rogersville remains unclear. These results are consistent with sedimentologic interpretations of Rogersville core that show moderate but consistent levels of bioturbation, current transport, storm event beds consistent with deposition in an oxic to slightly dysoxic environment.

Enrichment factors calculated for 8 trace elements show no or limited enrichment in these redox-sensitive elements. Additional data collection is planned to provide a more consistent dataset across wells to improve comparison and regional interpretation of geochemical proxies.

References

Algeo, T.J., and Maynard, J.B., 2004, Trace element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems: Chemical Geology, v. 206, p. 289–318, doi: 10.1016/j.chemgeo.2003.12.009.

Algeo, T.J. and Maynard, J.B., 2008, Trace-metal covariation as a guide to water-mass conditions in ancient anoxic marine environments: Geosphere, v. 4, p. 872-887.

Gill, B.C., Dahl, T.W., Hammarlund, E.U., LeRoy, M.A., Gordon, G.W., Canfield, D.E., Anbar, A.D., and Lyons, T.W., 2021, Redox dynamics of later Cambrian oceans: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 581, p. 1-15.

Hasson, K. O., and C. S. Haase, 1988, Lithofacies and paleogeography of the Conasauga Group (Middle and Late Cambrian) in the Valley and Ridge Province of East Tennessee: Geological Society of America Bulletin, v. 100, p. 234 – 246.

Hatch, J.R., Leventhal, J.S., 1992. Relationship between inferred redox potential of the depositional environment and geochemistry of the Upper Pennsylvanian (Missourian) stark shale member of the Dennis Limestone, Wabaunsee County, Kansas, USA. Chem. Geol. 99, 65– 82.

Jones, B., and Manning, D.A.C., 1994, Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones. Chem. Geol. 111, 111 –129.

Lyons, T.W. and Severmann, S., 2006, A critical look at iron paleoredox proxies: New insights from modern euxinic marine basins: Geochimica et Cosmochimica Acta, v. 70, p. 5698-5722.

Raiswell, R., Buckley, F., Berner, R.A., Anderson, T.F., 1988. Degree of pyritization of iron as a paleoenvironmental indicator of bottom-water oxygenation. J. Sediment. Petrol. 58 (5), 812–819.

Rankey, E.C., Walker, K.R., and Srinivasan, K, 1994, Gradual establishment of Iapetan “passive” margin sedimentation: stratigraphic consequences of Cambrian episodic tectonism and eustasy, southern Appalachians: Jour. Of Sed. Research, v. B64, p. 298-310.

Read, J. Fred, and John E. Repetski, 2012, Cambrian – lower Middle Ordovician passive carbonate margin, southern Appalachians, in J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan, and C. A. Sternbach, eds., The great American carbonate bank: The geology and economic resources of the Cambrian –Ordovician Sauk megasequence of Laurentia: AAPG Memoir 98, p. 357 – 382

Rimmer, S.M., 2004, Geochemical paleoredox indicators in Devonian–Mississippian black shales, Central Appalachian Basin (USA), Chemical Geology, v. 206, p. 373– 391.

Rimmer, S.M., Thompson, J.A., Goodnight, S.A., and Robl, T.L., 2004. Multiple controls on the preservation of organic matter in Devonian-Mississippian marine black shales: geochemical and petrographic evidence: Palaegeography, Palaeoclimatology, Palaeoecology, v. 215, p. 125-154.

Tribovillard, N., Algeo, T.J., Lyons, T., and Riboulleau, A., 2006, Trace metals as paleoredox and paleoproductivity proxies: An update: Chemical Geology, v. 232, p. 12-32.

Tyson, R.V., 1995, Sedimentary Organic Matter, Organic facies and palynofacies: Chapman and Hall, London, 615 p.

Wedepohl, K.H., 1971. Environmental influences on the chemical composition of shales and clays. In: Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C. (Eds.), Physics and Chemistry of the Earth, vol. 8. Pergamon, Oxford, pp. 307– 331.

k. Task 7.5 – Bitumen reflectance microscopic analysis*

Cortland F. Eble, PhD

Kentucky Geological Survey, University of Kentucky

Lexington, Ky.

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 3 months of work out of the expected and budgeted 18-month research plan.)

Introduction

Twenty-five samples of Conasauga Shale were analyzed using reflected light on polished surfaces, primarily to help determine the level of thermal maturity via solid bitumen reflectance using an oil immersion objective (BR_o). The samples were collected as drill core and core cuttings from exploration boreholes in Garrard, Morgan, Leslie, Johnson and Lawrence Counties, Kentucky, and Wayne County, West Virginia. Additional geochemical data was obtained from archived well records to provide a better assessment of total organic carbon present in the Conasauga Shale in Kentucky and West Virginia.

Methods, Geochemistry

Total carbon (TC) and sulfur (TS) values were determined using a Leco SC-144DR carbon/sulfur analyzer following procedures outlined in ASTM D4239-18e1 (ASTM, 2018). Total inorganic carbon (TIC) values were obtained using a UIC CM5014 CO_2 coulometer equipped with a CM5130 acidification module. Total organic carbon (TOC) values were obtained by difference, where: TOC = TC – TIC.

Methods, Organic Petrology

Petrographic pellets were constructed according to ASTM D2797/D2797M-11a (ASTM, 2019). Random reflectance measurements were obtained following ASTM D7708-14 (ASTM, 2014) on solid bitumen using a Zeiss Universal microscope, fitted with a Zeiss epi 40x oil immersion objective and a 1.6x magnification changer (combined magnification 640x). Cargille type FF (fluorescence free) immersion oil (ne = 1.518, ve = 42) was used. White light was supplied by an Osram Xenophot HLX 12V, 100W bulb. Ultraviolet light was provided by a Lumen Dynamics 120 W, high-pressure metal halide arc lamp, used in conjunction with a Zeiss 09 filter set (450-490 nm excitation, 510 nm beam splitter, and 515 nm emission filters).

Bitumen reflectance measurements were acquired by first calibrating a photomultiplier tube (PMT) using Schott glass reflectance standard LaSF6-961-349 (1.662 %), and then collecting a minimum of 50 reflectance values on solid bitumen particles. Measured bitumen reflectance values (BR_o) were converted to vitrinite reflectance equivalent values ($VR_{equivalent}$) using the conversion formula of Jacob (1989), where: $VR_{equivalent} = (BR_{o\ measured} * 0.618) + 0.4$.

Results, Geochemistry

Historical geochemical results for wells drilled in Kentucky and West Virginia are summarized by county in table 1. Total organic carbon contents (TOC) for a majority of the samples are very low (<0.5 wt.%). Of the 574 records with geochemical data examined, only 50 (or 8.7 %) had TOC values > 1 wt. % (Table 1). Programmed pyrolysis (aka. Rock Eval) data show wide ranges of individual parameter values (e.g., OI, HI, PI, Tmax), which is likely the result of low TOC. Tmax values, in particular, vary significantly and commonly produce negative values when used to calculate percent reflectance using the conversion formula of Jarvie et al (2001). The average occurrence of TOC in the Conasauga Shale, by county, is shown in Fig. 1. From this diagram, it can be seen that most of the counties with geochemical data from historical drilling have average TOC values <0.5 wt. %. Only two counties, Garrard, Kentucky (n = 3) and Wayne, West Virginia (n = 41), have average TOC values >1.0 wt. %. This changes slightly when the maximum TOC are graphed in a similar manner, with seven counties having maximum TOC >1.0 wt. % (Fig. 2).

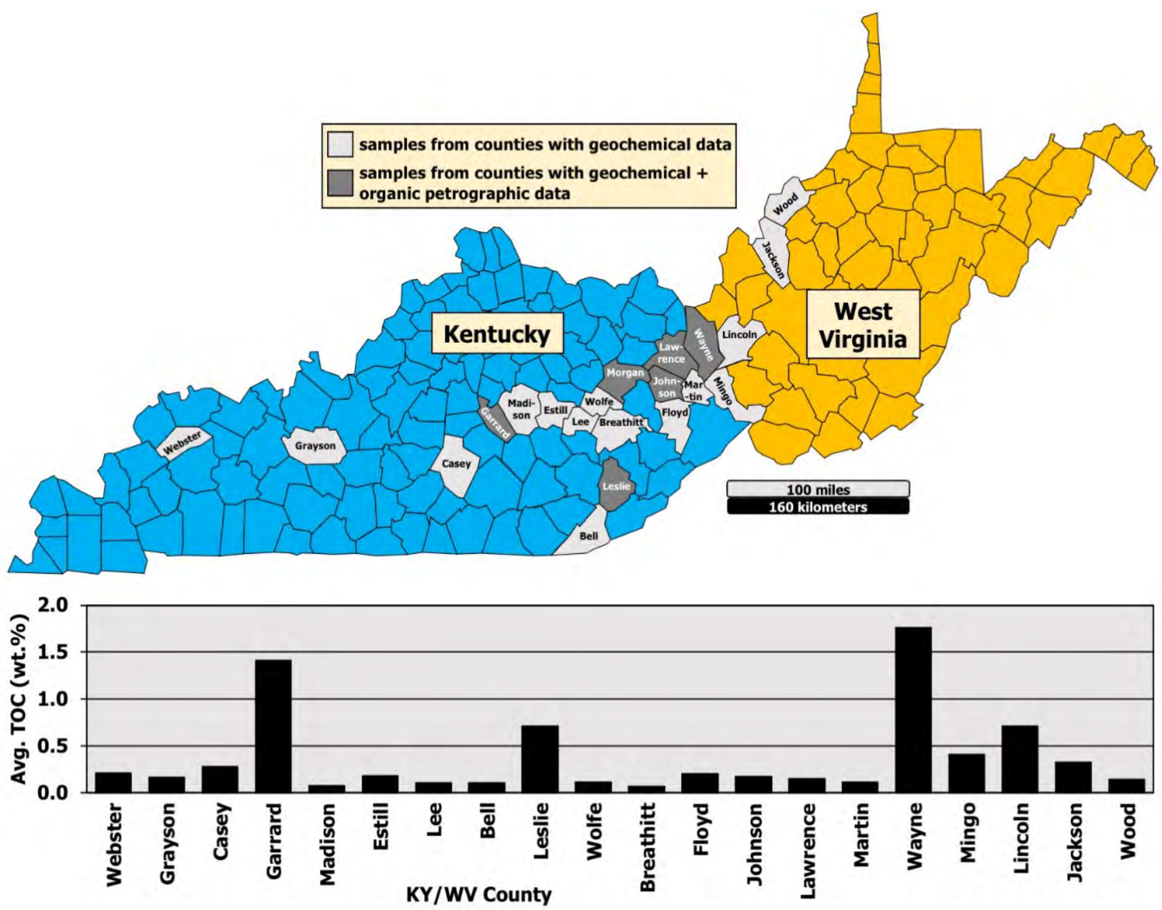


***Figure 1**. Distribution of average TOC in Kentucky and West Virginia Counties with geochemical data.*

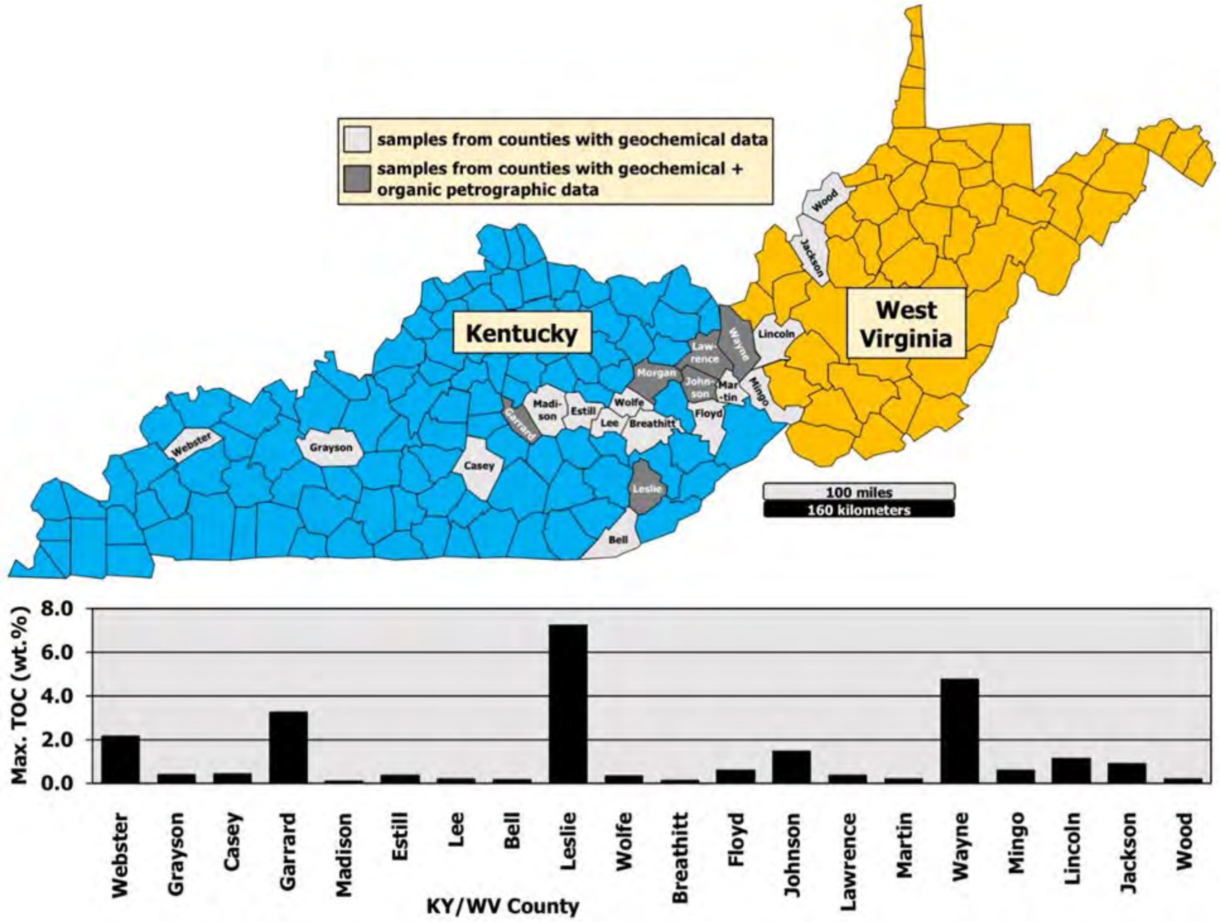


Figure 2*. Distribution of maximum TOC in Kentucky and West Virginia Counties with geochemical data.*

<u>Results, Organic Petrography</u>

Twenty-five samples of Conasauga Shale were examined petrographically with white and ultraviolet reflected light on polished surfaces (Table 2). One sample from Lawrence County, Kentucky contained insufficient organic material for analysis. Another sample of drill-cuttings from Leslie County, Kentucky contained abundant contamination from the overlying Ohio Shale. The removal of these two samples resulted in 23 samples of Conasauga Shale being analyzed petrographically. The most common form of organic material in the samples is solid bitumen. Solid bitumen is a common constituent of many petroleum-bearing sedimentary rocks, forming from the alteration of kerogen. Three morphologies of solid bitumen were observed. One had a very smooth surface while another was more granular in appearance (Figs. 3 and 4). Reflectance measurements were acquired from the smooth surface type only. A third type, which was much less common than the smooth and granular types, was very dark reflecting and may actually represent a zooclast (Fig. 5). The smooth and granular types of solid bitumen were commonly observed forming around grains of calcite and quartz. In the samples from Garrard and Morgan Counties, Kentucky, in the western portion of the study area, the level of thermal maturity was sufficiently low enough to detect the presence of alginate (mainly as lamalginite) in fluorescent light (Fig. 6). Alginite, and other liptinite macerals, fluoresce a yellow to red color in UV light up to about a level of 1.5 % BR_o, but are generally indetectable at higher levels of thermal maturity. Samples from Wayne

County, West Virginia, with BR_o values of 1.8 %, were exceptional in that dark red fluorescing liptinitic material was still observable.

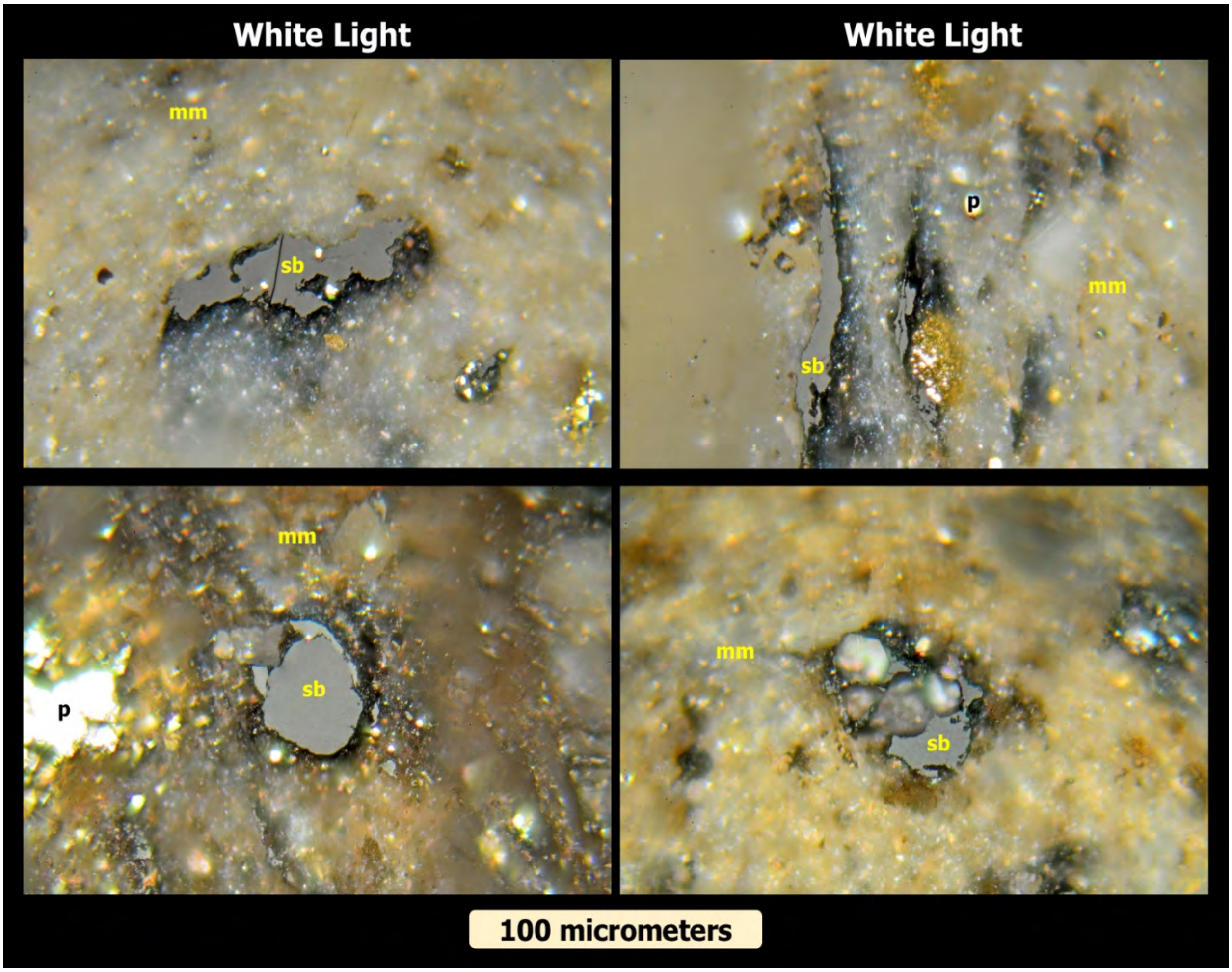


***Figure 3**. Examples of the smooth variety of solid bitumen (sb) in the Conasauga Shale. Reflectance measurements were collected from this type of solid bitumen. Mineral matter (mm) consists mainly of clays and quartz. Pyrite (p) is common throughout the Conasauga Shale.*

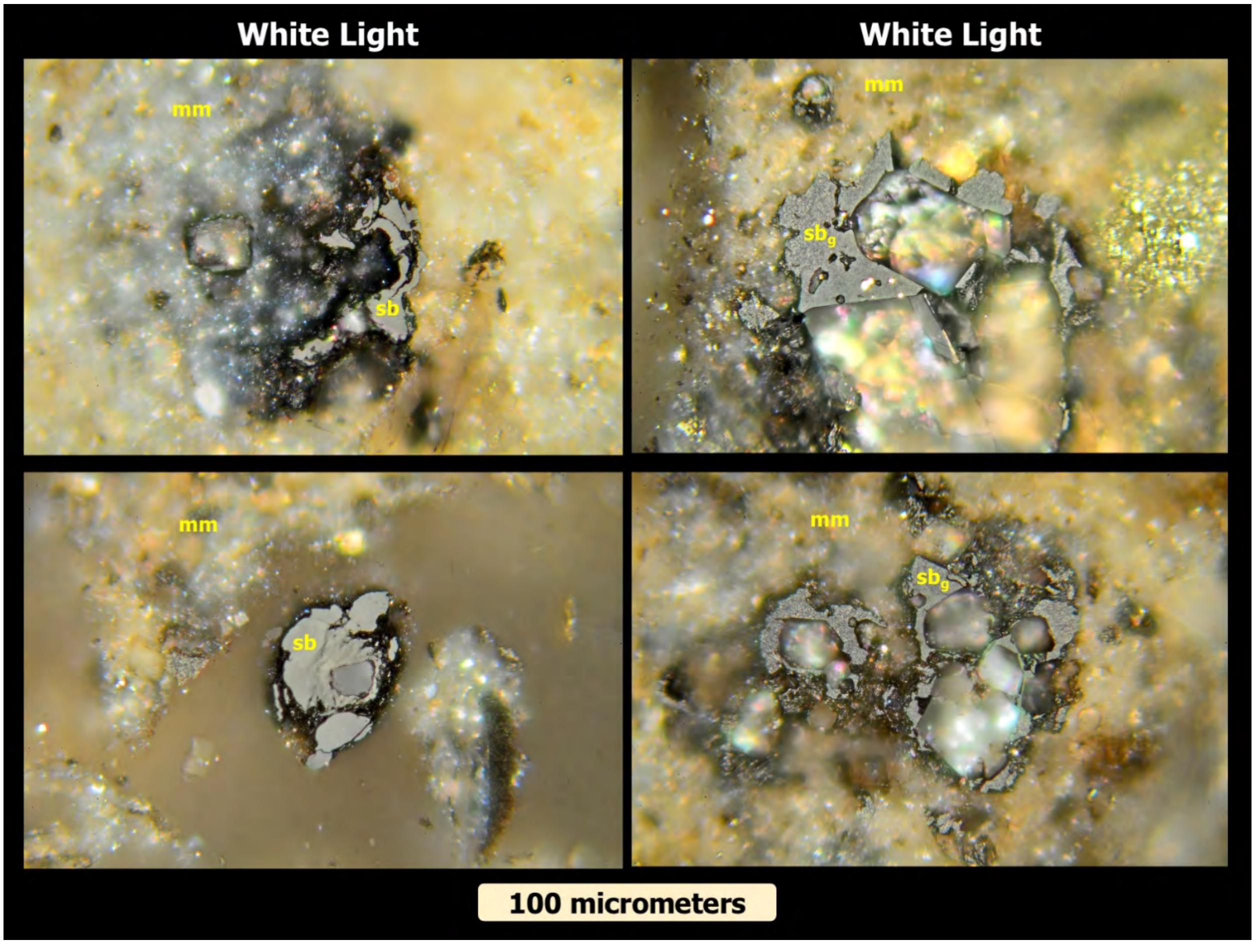


Figure 4. *Examples of the smooth (sb) and granular (sb_g) varieties of solid bitumen in the Conasauga Shale. Mineral matter (mm) consists mainly of clays and quartz.*

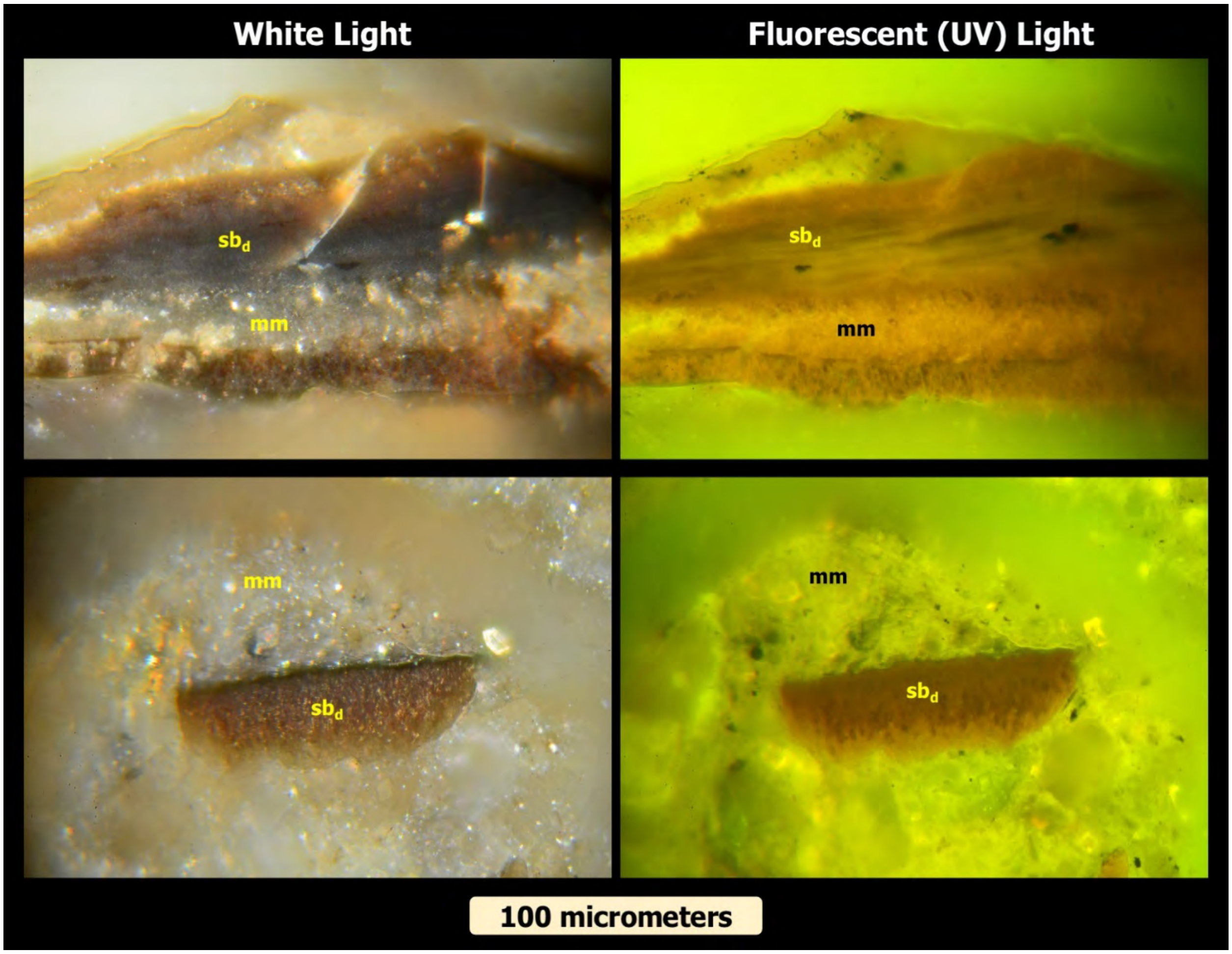


Figure 5. *Examples of the dark reflecting variety of solid bitumen (sb_d) in the Conasauga Shale in white and fluorescent light. Mineral matter (mm) consists mainly of clays and quartz.*

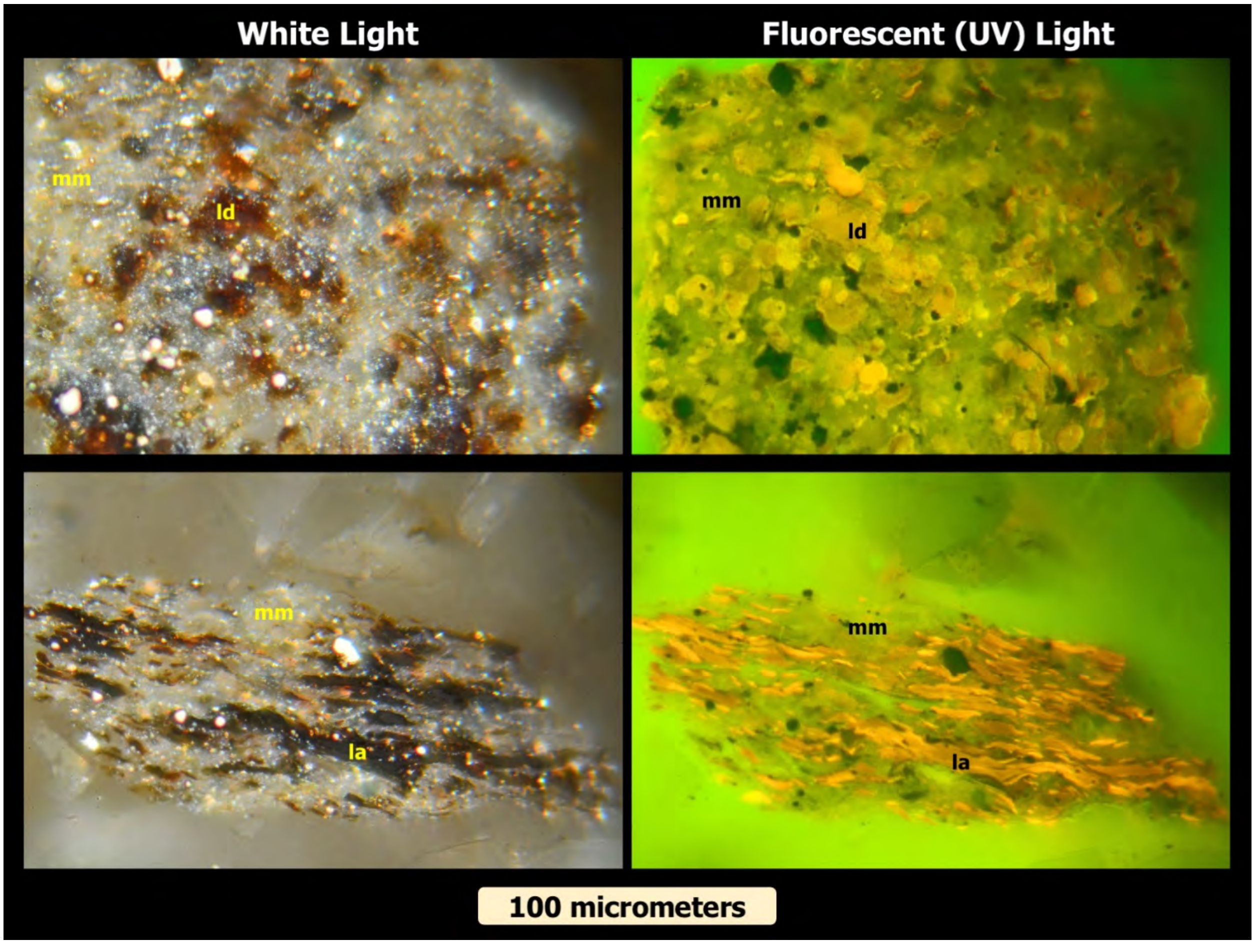


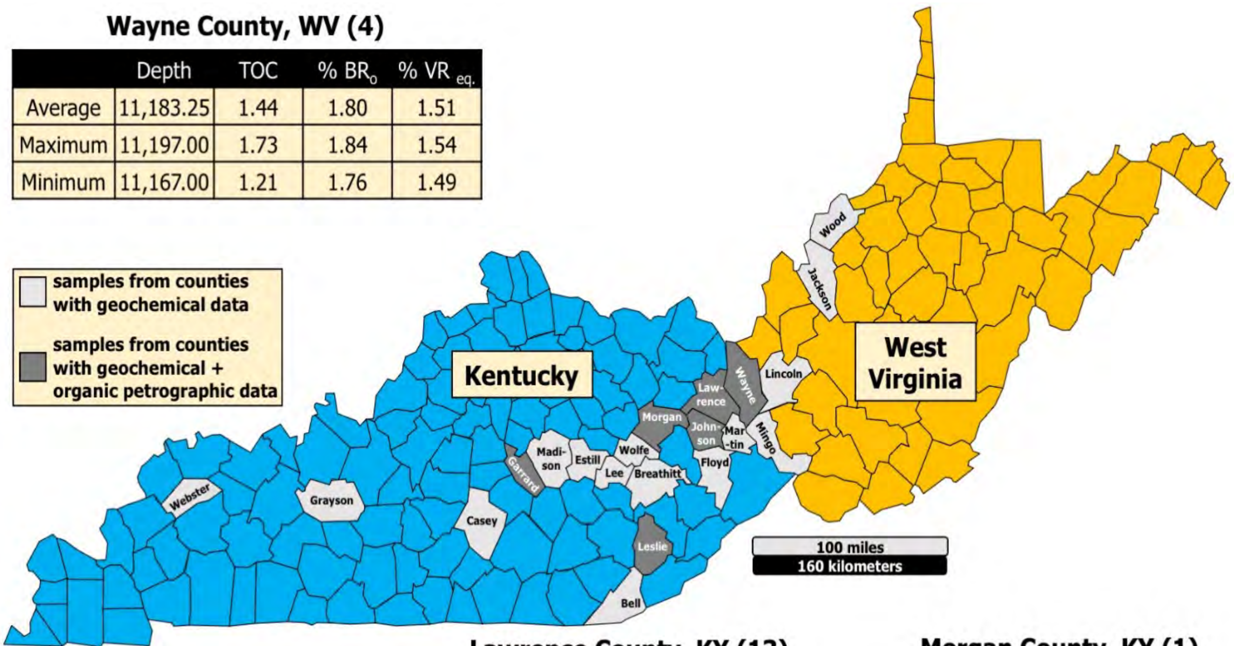
Figure 6*. Examples of the liptinite macerals liptodetrinite (ld) and lamalginite (la) in white and fluorescent light from the Conasauga Shale in Garrard County, Kentucky where the level of thermal maturity is relatively low (BR_o = 0.78 %, $VR_{equivalent}$ = 0.88 %).*

As with vitrinite, solid bitumen is sensitive to changes in temperature, changing from a dark gray in sediments with very low thermal maturity to lighter gray, and even white, with a progressive increase in temperature. As such, reflectance measurements on bitumen provide a very accurate way to measure thermal history. Moreover, they provide a convenient maturation proxy in pre-Devonian source rocks. Land flora, which produced vitrinite precursor material, began to evolve in the Late Silurian, but were simple in form and slender in composition. More robust forms with woody tissues, capable of producing vitrinite, did not appear until the Early to Middle Devonian. As such, most kerogen in pre-Devonian source rocks is believed to be of algal origin. Algal byproducts of microbial degradation also appear to represent a portion of the source material (Robert, 1981, 1988).

In practice, bitumen reflectance measurements are collected the same way vitrinite is measured. However, the maturation rate of bitumen is different than that of vitrinite. Bitumen matures more slowly than vitrinite up to a reflectance of 1.05 %, and then progresses more quickly than vitrinite with increasing thermal maturity. Because of this, bitumen reflectance values (BR_o) are routinely transposed to vitrinite equivalent values ($VR_{equivalent}$) using published formulae (Jacob, 1989; Landis and Castãno, 1995; Shoenherr et al., 2007). In this study, the conversion formula proposed by Jacob (1989) was found to be most suitable and is expressed as: $VR_{equivalent} = (BR_{o\ measured} * 0.618) + 0.4$. Bitumen reflectance values were the lowest in a single sample from a Garrard County, KY well (BR_o = 0.78 %) and highest in samples from Johnson (avg. BR_o = 2.08 %, n = 4) and Lawrence Counties (avg. BR_o = 2.08 %, n = 13) (Fig. 7). This west to east increase in thermal maturity parallels an increase in sample depth, with the Garrard County well sample having a depth of 4,628 ft (1,410.6 m), and the samples from Johnson and Lawrence Counties having depths between 10,580 and 15,906 ft (3,224.8 and 4,848.1 m) (Figs. 8 and 9).

Wayne County, WV (4)

	Depth	TOC	% BR_o	% $VR_{eq.}$
Average	11,183.25	1.44	1.80	1.51
Maximum	11,197.00	1.73	1.84	1.54
Minimum	11,167.00	1.21	1.76	1.49



Garrard County, KY (1)

Depth (ft)	TOC	% BR_o	% VR equivalent
4,628.00	3.26	0.78	0.88

Leslie County, KY (1)

Depth (ft)	TOC	% VR_o	% VR equivalent
8,140.00	2.70	0.75*	n/d

*measurements derived from Devonian-age Ohio shale borehole contamination.

Lawrence County, KY (13)

	Depth	TOC	% BR_o	% $VR_{eq.}$
Average	11,635.47	1.83	2.08	1.68
Maximum	15,906.00	1.14	2.27	1.80
Minimum	10,406.00	1.51	1.88	1.56

Johnson County, KY (4)

	Depth (ft)	TOC	% BR_o	% $VR_{eq.}$
Average	10,765.00	2.33	2.08	1.68
Maximum	10,950.00	4.31	2.17	1.74
Minimum	10,580.00	1.30	2.03	1.65

Morgan County, KY (1)

Depth (ft)	TOC	% BR_o	% VR equivalent
9,500.00	1.05	1.64	1.42

***Figure 7**. Reflectance summary for Kentucky and West Virginia samples.*

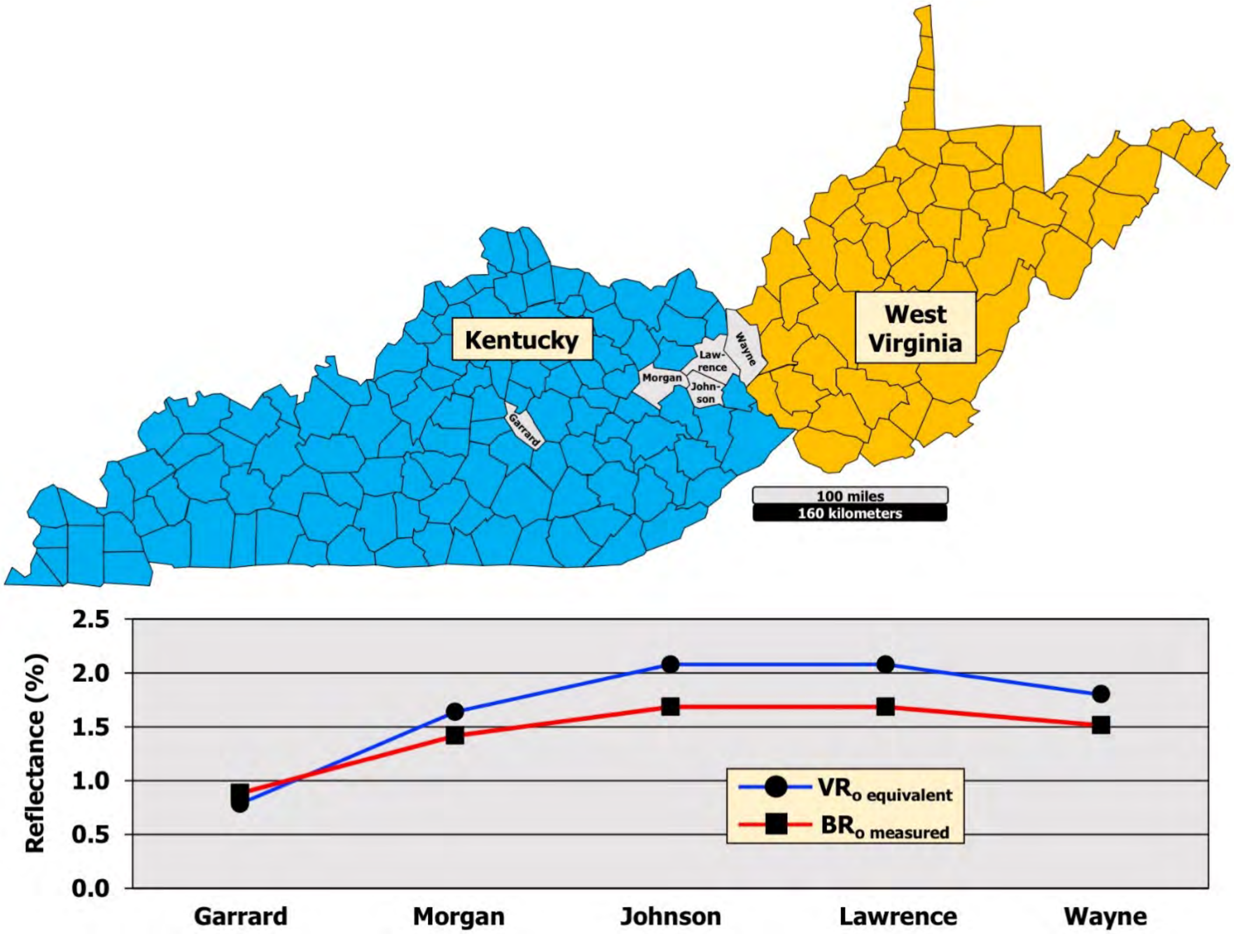
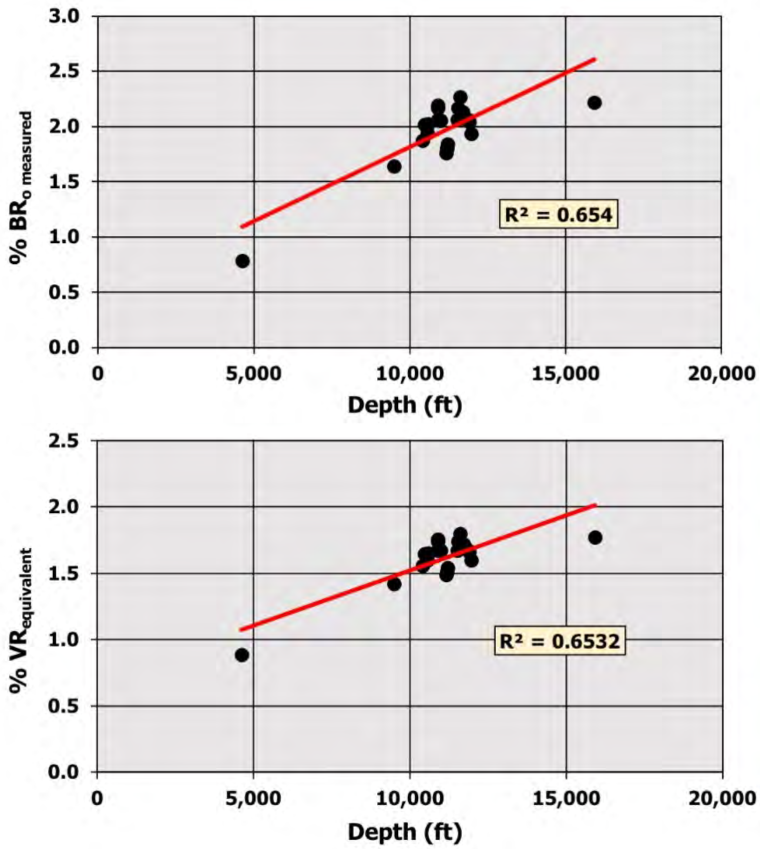


***Figure 8**. Solid bitumen reflectance diagram for the Conasauga Shale showing a west to east increase in reflectance.*



Depth (ft)	% BR_o	% VR_{eq}
4,628.00	0.78	0.88
9,500.00	1.64	1.42
10,406.00	1.88	1.56
10,475.00	2.02	1.65
10,568.00	1.94	1.60
10,580.00	2.03	1.65
10,900.00	2.06	1.67
10,900.50	2.17	1.74
10,902.00	2.19	1.75
10,950.00	2.05	1.67
10,977.10	2.06	1.67
11,167.30	1.76	1.49
11,178.30	1.80	1.51
11,191.00	1.80	1.51
11,197.30	1.84	1.54
11,519.50	2.06	1.67
11,546.00	2.17	1.74
11,606.50	2.27	1.80
11,707.00	2.13	1.72
11,868.76	2.06	1.67
11,895.54	2.04	1.66
11,960.82	1.94	1.60
15,906.00	2.22	1.77

$VR_{equivalent} = (BR_{measured} * 0.618) + 0.4$
(Jacob, 1989)

Figure 9*. Linear regression plots for measured bitumen reflectance ($BR_{o\ measured}$) and vitrinite equivalent reflectance ($VR_{equivalent}$) versus depth, showing an increase in the level of reflectance with increasing sample depth.*

<u>Summary</u>

The examination of 574 well records from Kentucky and West Virginia with geochemical data indicate that the Conasauga Shale contains minimal amounts of organic matter, with only 50 records (8.7 %) showing TOC >1 wt. %. Most of the organic matter in the Conasauga Shale occurs as solid bitumen with some samples showing the presence of alginate, mainly occurring as lamalginite in fluorescent light.

Bitumen reflectance (BR_o) analysis indicates the thermal maturity of the Conasauga Shale to vary from 0.78 % in the western part of the study area (Garrard County, Kentucky) to 2.27 % in the eastern part of the study area (Johnson and Lawrence Counties, Kentucky). Vitrinite reflectance equivalent values ($VR_{equivalent}$), calculated from the measured BR_o values, range from 0.88 % to 1.8 %. This west to east trend of increasing thermal maturity is paralleled by an increase in sample depth. In Garrard County, Kentucky, the analyzed sample came from a depth of 4,628 ft (1,410.6 m), whereas the samples analyzed from Johnson and Lawrence Counties, Kentucky came from depths between 10,580 and 15,906 ft (3,224.8 and 4,848.1 m). Future exploration and production from the Conasauga Shale in Kentucky and West Virginia will be challenging, as the unit is low in TOC. Although "pockets" with elevated TOC appear to exist, based on available data, these areas appear to be geographically constrained.

Table 1. *Geochemical data, summarized by county, for the Conasauga Shale in Kentucky and West Virginia.*

County	Depth	Depth									(S1*100) /		
Bell, KY	**Top**	**Base**	**S1**	**S2**	**S3**	**Tmax**	**Rcalc**	**HI**	**OI**	**S2/S3**	**TOC**	**PI**	**TOC**
Average	9,282.50	9,293.33	0.23	0.23	0.39	419.56	0.39	210.50	373.05	0.65	218.34	0.52	0.11
Maximum	9,530.00	9,550.00	0.27	0.35	0.57	506.10	1.95	300.86	644.70	1.58	315.19	0.73	0.16
Minimum	8,740.00	8,750.00	0.16	0.06	0.12	309.20	-1.59	55.05	111.11	0.18	134.15	0.44	0.07
Count	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
>1 % TOC	0.00												
Breathitt, KY													
Average	8,585.71	8,595.71	0.15	0.22	0.49	461.29	1.14	385.24	770.97	0.50	253.46	0.41	0.07
Maximum	10,150.00	10,160.00	0.19	0.27	0.74	488.00	1.62	812.50	1321.43	0.84	487.18	0.50	0.10
Minimum	6,930.00	6,940.00	0.10	0.17	0.31	407.00	0.17	208.79	375.00	0.23	154.76	0.33	0.03
Count	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
>1 % TOC	0.00												
Carter, KY													
Average	8,353.00	8,365.00											0.22
Maximum	8,600.00	8,610.00											0.99
Minimum	8,100.00	8,130.00											0.06
Count	10.00	10.00											10.00
>1 % TOC	0.00												
Casey, KY													
Average	7,240.92		0.04	0.09	0.09	389.50	-0.15	31.38	39.25	1.50	12.87	0.29	0.28
Maximum	7,253.00		0.06	0.14	0.22	497.00	1.79	42.11	115.79	3.50	17.00	0.33	0.41
Minimum	7,226.00		0.02	0.06	0.04	335.00	-1.13	21.56	9.79	0.36	6.62	0.20	0.18
Count	6.00		6.00	6.00	5.00	6.00	6.00	6.00	5.00	5.00	6.00	6.00	6.00
>1 % TOC	0.00												

Elliot, KY													
Average	7,991.43	8,382.95	0.07	1.70	0.22	431.76	0.61	193.07	487.38	2.43	98.17	0.28	0.33
Maximum	9,350.00	9,360.00	0.59	38.26	1.54	477.00	1.43	1,166.67	6,500.00	15.00	641.03	0.68	5.87
Minimum	5,700.00	5,800.00	0.01	0.01	0.01	370.00	-0.50	3.45	5.26	0.07	8.67	0.15	0.01
Count	77.00	56.00	46.00	46.00	45.00	37.00	37.00	46.00	45.00	37.00	38.00	41.00	77.00
>1 % TOC	2.00												
Estill, KY													
Average	6,381.06		0.02	0.14	0.05	438.63	0.74	84.11	36.11	5.51	12.29	0.12	0.18
Maximum	6,390.50		0.04	0.34	0.15	450.00	0.94	236.36	136.36	34.00	36.36	0.23	0.34
Minimum	6,370.00		0.00	0.05	0.00	426.00	0.51	31.00	0.00	0.00	0.00	0.00	0.11
Count	8.00		8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
>1 % TOC	0.00												
Floyd, KY													
Average	9,029.38	9,039.38	0.10	0.15	0.36	355.40	-0.76	104.36	282.89	0.48	75.48	0.39	0.21
Maximum	11,540.00	11,550.00	0.21	0.32	0.64	427.00	0.53	306.12	1,777.78	0.95	257.52	0.51	0.60
Minimum	7,840.00	7,850.00	0.05	0.10	0.18	328.00	-1.26	26.59	60.25	0.17	15.95	0.24	0.04
Count	32.00	32.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	32.00
>1 % TOC	0.00												
Garrard, KY													
Average	4,610.93		0.30	5.58	0.25	442.67	0.81	335.00	44.67	21.23	26.00	0.07	1.41
Maximum	4,628.80		0.55	13.61	0.35	446.00	0.87	417.00	107.00	38.89	43.00	0.11	3.26
Minimum	4,576.00		0.05	0.65	0.11	438.00	0.72	232.00	11.00	2.17	17.00	0.04	0.28
Count	3.00		3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
>1 % TOC	1.00												
Grayson, KY													
Average	9,811.18	9,821.18	0.03	0.09	0.26	350.71	-0.85	65.50	185.59	0.57	24.33	0.27	0.17

Maximum	12,590.00	12,600.00	0.06	0.16	0.57	432.00	0.62	175.00	600.00	1.60	62.23	0.33	0.39
Minimum	7,890.00	7,900.00	0.01	0.05	0.05	321.00	-1.38	23.53	44.54	0.12	8.64	0.14	0.04
Count	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00
>1 % TOC	0.00												
Johnson, KY													
Average	9,436.95	9,770.16	0.07	0.13	0.44	385.15	-0.23	155.09	939.39	0.32	108.31	0.43	0.17
Maximum	13,150.00	13,160.00	0.29	1.04	1.26	506.00	1.95	700.00	5,400.00	2.00	520.83	0.84	1.44
Minimum	6,270.60	6,320.00	0.02	0.01	0.03	301.00	-1.74	6.17	66.83	0.03	5.45	0.14	0.01
Count	140.00	127.00	73.00	73.00	73.00	55.00	55.00	73.00	73.00	71.00	73.00	73.00	140.00
>1 % TOC	2.00												
Lawrence, KY													
Average	9,964.71	9,974.71	0.06	0.13	0.50	410.91	0.24	123.48	551.70	0.28	67.18	0.36	0.15
Maximum	11,570.00	11,580.00	0.13	0.31	0.97	450.00	0.94	600.00	1,901.96	0.54	433.33	0.75	0.35
Minimum	7,680.00	7,690.00	0.03	0.01	0.26	330.00	-1.22	20.41	207.32	0.02	18.99	0.21	0.03
Count	34.00	34.00	24.00	24.00	24.00	22.00	22.00	24.00	24.00	24.00	24.00	24.00	34.00
>1 % TOC	0.00												
Lee, KY													
Average	6,855.83	6,865.83	0.14	0.10	0.29	396.73	-0.02	92.54	389.84	1.32	102.67	0.51	0.11
Maximum	8,130.00	8,140.00	0.61	0.24	0.47	437.20	0.71	178.57	1,740.74	12.00	324.47	0.72	0.19
Minimum	5,560.00	5,570.00	0.02	0.02	0.01	330.00	-1.22	29.70	10.42	0.06	29.88	0.25	0.03
Count	12.00	12.00	12.00	12.00	12.00	10.00	10.00	12.00	12.00	12.00	12.00	12.00	12.00
>1 % TOC	0.00												
Leslie, KY													
Average	7,970.00	7,981.85	0.29	1.39	0.25	457.20	1.07	128.31	87.06	5.21	69.76	0.32	0.72
Maximum	9,390.00	9,400.00	3.24	32.08	0.81	514.00	2.09	443.59	462.26	82.26	296.38	0.64	7.23
Minimum	7,200.00	7,210.00	0.05	0.14	0.08	308.00	-1.62	24.07	5.39	0.32	8.33	0.09	0.09

Count	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00	54.00
>1 % TOC	10.00												
Madison, KY													
Average	4,770.00		0.02	0.04	0.10	456.50	1.06	47.88	125.00	0.20	26.65	0.39	0.08
Maximum	4,770.00		0.02	0.05	0.10	463.00	1.17	70.77	125.00	0.20	28.31	0.50	0.08
Minimum	4,770.00		0.02	0.02	0.10	450.00	0.94	25.00	125.00	0.20	25.00	0.29	0.07
Count	2.00		2.00	2.00	1.00	2.00	2.00	2.00	1.00	1.00	2.00	2.00	2.00
>1 % TOC	0.00												
Martin, KY													
Average	10,367.69	10,377.69	0.15	0.21	0.46	435.23	0.67	250.39	688.43	0.49	166.58	0.41	0.11
Maximum	11,920.00	11,930.00	0.27	0.32	0.65	488.00	1.62	633.33	2,166.67	0.97	426.48	0.57	0.20
Minimum	8,610.00	8,620.00	0.07	0.12	0.29	374.00	-0.43	92.20	201.01	0.19	92.39	0.26	0.02
Count	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00
>1 % TOC	0.00												
Webster, KY													
Average	13,885.00	13,895.00	0.39	0.20	0.12	431.63	0.61	30.91	192.79	0.82	16.26	0.14	0.22
Maximum	15,050.00	15,060.00	0.39	2.81	0.28	500.00	1.84	131.31	533.33	10.04	18.22	0.17	2.14
Minimum	12,510.00	12,520.00	0.39	0.01	0.06	331.00	-1.20	5.56	13.08	0.06	14.29	0.12	0.03
Count	16.00	16.00	1.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	2.00	2.00	16.00
>1 % TOC	1.00												
Wolfe, KY													
Average	8,813.00	8,714.29	0.03	0.06	0.29	361.00	-0.66	61.33	655.45	0.39	34.47	0.37	0.11
Maximum	12,211.00	11,680.00	0.05	0.14	1.19	521.00	2.22	300.00	5,823.53	1.56	198.61	0.75	0.32
Minimum	6,710.00	6,720.00	0.01	0.01	0.07	299.00	-1.78	10.00	28.60	0.02	10.94	0.18	0.01
Count	49.00	35.00	31.00	31.00	31.00	24.00	24.00	31.00	31.00	31.00	31.00	31.00	49.00
>1 % TOC	0.00												

Jackson, WV													
Average	14,910.84		0.17	0.11	0.17	413.83	0.29	31.70	66.37	0.84	67.13	0.56	0.33
Maximum	16,493.00		1.62	0.41	0.44	428.00	0.54	88.00	200.00	4.14	810.00	0.95	0.88
Minimum	9,294.80		0.02	0.01	0.01	392.00	-0.10	7.69	6.25	0.01	9.00	0.30	0.09
Count	28.00		28.00	28.00	24.00	6.00	6.00	28.00	24.00	24.00	28.00	28.00	28.00
>1 % TOC	0.00												
Lincoln, WV													
Average	15,118.00		0.16	0.12	0.10	359.75	-0.68	22.25	20.50	1.37	33.75	0.60	0.72
Maximum	16,906.00		0.23	0.22	0.15	400.00	0.04	46.00	46.00	2.00	77.00	0.68	1.12
Minimum	13,650.00		0.10	0.06	0.06	299.00	-1.78	8.00	8.00	0.47	18.00	0.51	0.13
Count	4.00		4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
>1 % TOC	1.00												
Mingo, WV													
Average	16,236.17		0.10	0.07	0.27			21.00	93.33	0.02	25.67	0.57	0.41
Maximum	16,239.50		0.15	0.09	0.28			33.00	180.00	0.02	27.00	0.62	0.58
Minimum	16,233.50		0.04	0.05	0.27			15.00	46.00	0.01	24.00	0.50	0.15
Count	3.00		3.00	3.00	3.00			3.00	3.00	3.00	3.00	3.00	3.00
>1 % TOC	0.00												
Wayne, WV													
Average	11,414.87		0.91	1.16	0.49	443.05	0.81	59.32	31.41	4.52	50.19	0.41	1.76
Maximum	13,734.50		4.55	4.83	4.25	481.00	1.50	112.50	111.55	28.41	96.43	0.75	4.75
Minimum	10,580.00		0.03	0.01	0.01	299.00	-1.78	7.00	3.58	0.13	1.60	0.03	0.09
Count	43.00		41.00	43.00	43.00	39.00	39.00	43.00	43.00	27.00	39.00	41.00	43.00
>1 % TOC	33.00												
Wood, WV													
Average	13,133.60		0.31	0.20	0.26			129.00	206.33	0.72	172.00	0.44	0.15

Maximum	13,139.80		0.31	0.39	0.28			246.00	337.00	1.39	172.00	0.44	0.18
Minimum	13,128.00		0.31	0.01	0.23			12.00	127.00	0.04	172.00	0.44	0.08
Count	3.00		1.00	2.00	3.00			2.00	3.00	2.00	1.00	1.00	3.00
>1 % TOC	0.00												
Scioto, OH													
	5,137.80		0.03	0.06	0.11	299.00	-1.78	50.00	92.00	0.55	25.00	0.33	0.12

Table 2. *Thermal maturity data, for the Conasauga Shale in Kentucky and West Virginia.*

KGS ID	County	State	Depth	TOC (wt.%)	Avg. % BR_o	Max. % BR_o	Min. % BR_o	Std Deviation	Calculated % Vreq.
CS-300	Garrard	KY	4,628.0	3.26	0.78	0.93	0.63	0.08	0.88
CS-301	Leslie	KY	8,140.0	2.70	0.75*	0.81	0.64	0.04	n/d*
CS-302	Morgan	KY	9,500.0	1.05	1.64	1.76	1.50	0.07	1.42
CS-303	Johnson	KY	10,580.0	4.31	2.03	2.17	1.88	0.08	1.65
CS-304	Johnson	KY	10,950.0	1.94	2.05	2.19	1.90	0.07	1.67
CS-305	Lawrence	KY	10,406.0	1.63	1.88	1.99	1.71	0.07	1.56
CS-306	Lawrence	KY	10,475.0	2.69	2.02	2.16	1.87	0.08	1.65
CS-307	Lawrence	KY	10,568.0	2.07	1.94	2.07	1.79	0.07	1.60
CS-308	Lawrence	KY	10,902.0	1.51	2.19	2.33	2.03	0.08	1.75
CS-308A	Lawrence	KY	10,900.0	1.51	2.06	2.21	1.92	0.08	1.67
CS-309	Lawrence	KY	11,707.0	1.60	2.13	2.28	1.89	0.10	1.72
CS-310	Johnson	KY	10,900.5	1.76	2.17	2.28	1.99	0.07	1.74
CS-311	Johnson	KY	10,977.1	1.30	2.06	2.24	1.81	0.13	1.67
CS-312	Lawrence	KY	11,868.8	1.99	2.06	2.21	1.87	0.09	1.67
CS-313	Lawrence	KY	11,895.5	2.41	2.04	2.22	1.83	0.11	1.66
CS-314	Lawrence	KY	11,960.8	2.03	1.94	2.12	1.73	0.09	1.60
CS-315	Lawrence	KY	15,720.0	1.14	n/d**	n/d**	n/d**	n/d**	n/d**
CS-316	Lawrence	KY	11,519.5	1.74	2.06	2.19	1.90	0.07	1.67
CS-317	Lawrence	KY	11,546.0	1.56	2.17	2.30	1.98	0.09	1.74
CS-318	Lawrence	KY	11,606.5	2.11	2.27	2.41	2.08	0.08	1.80
CS-319	Lawrence	KY	15,906.0	1.59	2.22	2.39	2.03	0.09	1.77
X1 Smith	Wayne	WV	11,167.3	1.73	1.76	1.89	1.61	0.09	1.49
X1 Smith	Wayne	WV	11,178.3	1.21	1.80	1.98	1.69	0.10	1.51
X1 Smith	Wayne	WV	11,191.0	1.51	1.80	2.07	1.71	0.11	1.51
X1 Smith	Wayne	WV	11,197.3	1.29	1.84	2.15	1.78	0.09	1.54

* vitrinite reflectance (VR_o) measurements from Devonian shale contamination

**insufficient organic material for analysis

References

ASTM D7708-14, 2014, Standard test method for microscopical determination of the reflectance of vitrinite dispersed in sedimentary rocks, ASTM International, West Conshohocken, PA, USA, www.astm.org.

ASTM D4239-18e1, 2018, Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion, ASTM International, West Conshohocken, PA, USA, www.astm.org.

ASTM D2797/D2797M-11a, 2019, Standard practice for preparing coal samples for microscopical analysis by reflected light, ASTM International, West Conshohocken, PA, USA, www.astm.org.

Jacob, H., 1989, Classification, structure, genesis, and practical importance of natural solid oil bitumen (migrabitumen): International Journal of Coal Geology, v. 11, no. 1, p. 65-79.

Jarvie, D.M., B.L. Claxton, F. Henk, and J.T. Breyer, 2001, Oil and shale gas from the Barnett Shale, Fort Worth basin, Texas: AAPG Annual Meeting Program, v. 10, p. A100.

Landis, C.R., and J.R. Castaño, 1995, Maturation and bulk chemical properties of a suite of solid hydrocarbons: Organic Geochemistry, v. 22, p. 137–149.

Robert, P., 1981, Classification of organic matter by means of fluorescence; application to hydrocarbon source rocks: International Journal of Coal Geology, v. 1-2, p. 101-137.

Robert, P., 1988, Organic metamorphism and geothermal history; microscopic history of organic matter and thermal evolution of sedimentary basins: Elf-Aquitaine and D. Reidel (Kluwer Academic Publishers), Norwell, MA, USA, 291 p.

Schoenherr, J., R. Littke, J.L. Urai, P.A. Kukla, and Z. Rawahi, 2007, Polyphase thermal evolution in the Infra-Cambrian Ara Group (South Oman Salt Basin) as deduced by maturity of solid reservoir bitumen: Organic Geochemistry, v. 38, p. 1293–1318.

l. Task 7.9 – Programed pyrolysis and source rock extract geochemistry*

By John Hickman, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

(*Note: Because of the ending of this project prior to Budget Period 2, this task was only funded to complete 3 months of work out of the expected and budgeted 18-month research plan.)

Introduction

Programed pyrolysis is a common laboratory process used to determine the organic richness and thermal maturity of potential hydrocarbon source rocks (Tissot and Welte, 1984). This analytical method requires geologic sample material of sufficient organic richness (> 1 wt%) in order to produce reliable results. Therefore, this task had to be idle while waiting on the %TOC results from Task 7.1. Once those values were determined, twenty geological samples (Table 1) from five Kentucky wells were collected, inventoried, and shipped to GeoMark Labs for pyrolysis (using a RockEVAL apparatus). The results of these analyses were returned near the end of the CSRC project term, so unfortunately no further interpretation of these results was performed.

Table 1. *List of programed pyrolysis samples for CSRC.*

ID#	KGS_Rec#	Well_Name	County	State	TOP	BASE	sample type
CS-320	11665	Inland Gas 542 Young, W	Lawrence	KY	9510	9520	cuttings
CS-321	14808	Monitor Petroleum 1 Ison, F&E	Morgan	KY	9500	9510	cuttings
CS-322	120354	Hay Expl 1 Blue Ribbon Coal	Johnson	KY	10550	10560	cuttings
CS-323	120354	Hay Expl 1 Blue Ribbon Coal	Johnson	KY	10890	10900	cuttings
CS-324	120354	Hay Expl 1 Blue Ribbon Coal	Johnson	KY	10950	10960	cuttings
CS-325	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	10760	10770	cuttings
CS-326	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	10980	10990	cuttings
CS-327	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	11898.2	11898.2	whole core
CS-328	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	11909.2	11909.2	whole core
CS-329	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	11952.4	11952.4	whole core
CS-330	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	11957.2	11957.2	whole core
CS-331	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	12160	12170	cuttings
CS-332	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	13200	13210	cuttings
CS-333	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	13320	13330	cuttings
CS-334	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	13480	13490	cuttings
CS-335	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	15000	15010	cuttings
CS-336	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	15320	15330	cuttings
CS-337	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	15720	15730	cuttings
CS-338	145803	Chesapeake LAW1 JH Northup Est	Lawrence	KY	15800	15810	cuttings
CS-339	145815	Bruin Expl 1H Walbridge	Lawrence	KY	12940	12950	cuttings

References

Tissot, B., P., Welte, D., H., 1984, Petroleum Formation and Occurrence, 2 ed.: New York, Springer-Verlag, 699 p.

m. Task 7.10 – Log Analysis of the Rogersville Shale Wells

By J. Richard Bowersox, PhD

University of Kentucky – Kentucky Geological Survey

Lexington, Ky.

Introduction

Six wells were drilled in the Rogersville Shale play between 2014 and 2017 (Figures 1 and 2), however the Chesapeake 1 Stephens well did not encounter shale within the Rogersville interval, and the Cabot 50 Amherst did not reach the Rogersville at its total depth (TD). Of the remaining four wells, the quality of EQT (drilled as Horizontal Technology Energy Company) 572360 Caudill well's geophysical logs ("logs") were compromised by wellbore washouts which led to poor data quality through the interval of interest (Figure 2). Petrophysical well log analysis ("log analysis") was thus performed on three Rogersville wells whose logs' quality were suitable for analysis: the Cimarex (operating as Bruin Exploration) 1 Young and 1 Walbridge wells and the Chesapeake 1 Northup well. All three of these wells had supporting datasets of core analysis and total organic carbon (TOC) analysis as well as X-ray diffraction mineralogy (XRD).

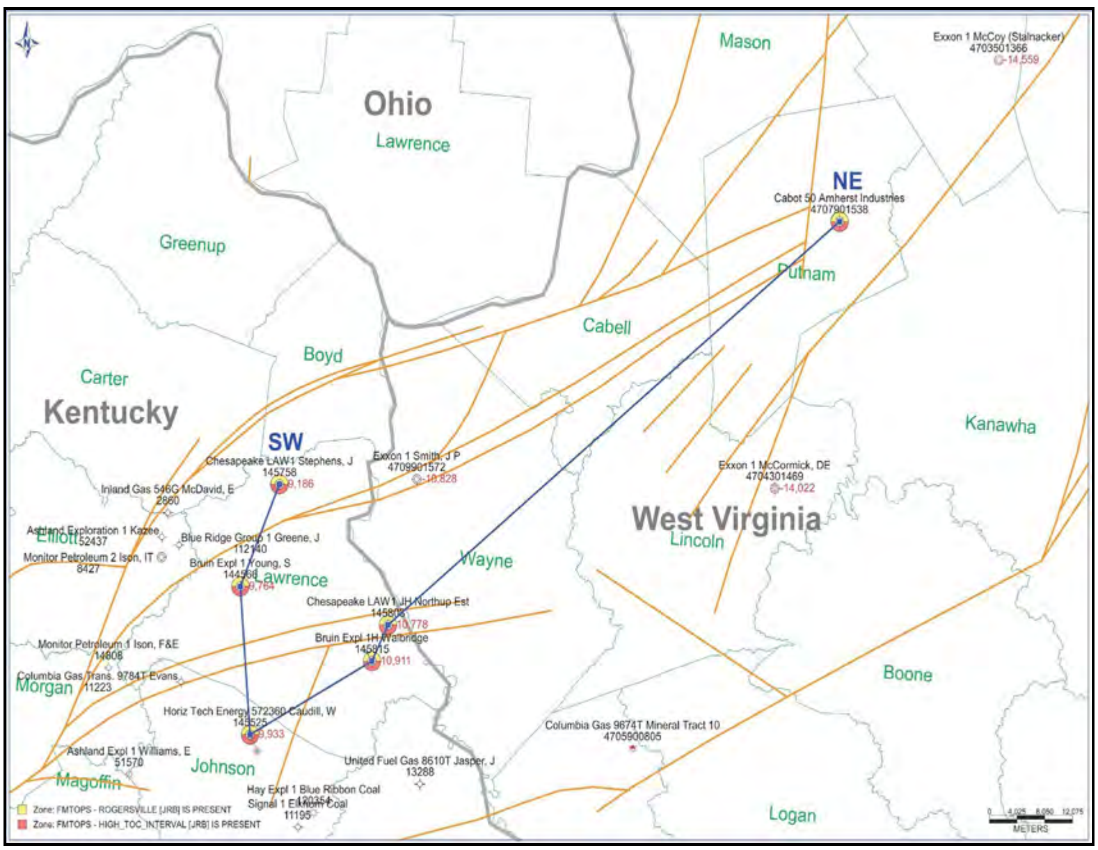


__Figure 1.__ Location of the Rogersville Shale evaluation, northeast Kentucky and southwest West Virginia showing the line of cross section in Figure 2. Tan lines represent preliminary interpretations of basement fault system locations.

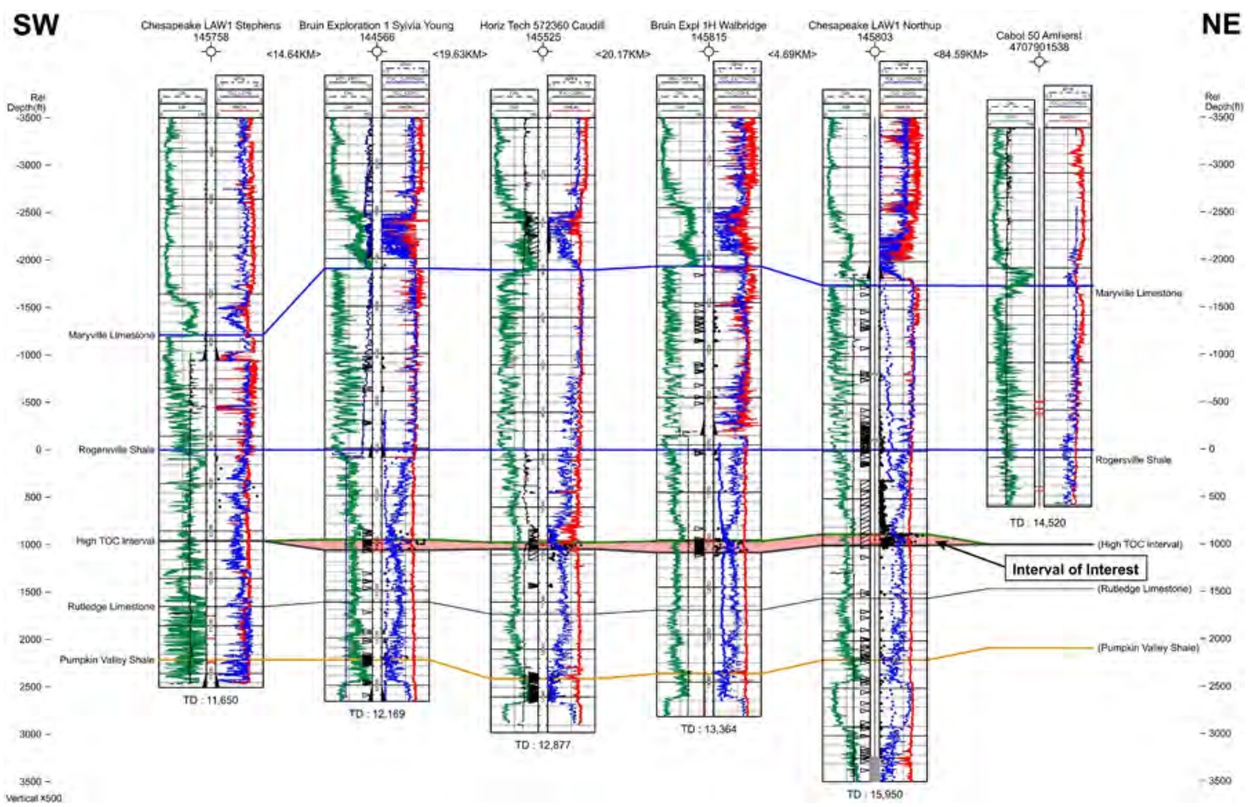


Figure 2. *SW–NE stratigraphic cross section through the Rogersville Shale exploratory wells in northeast Kentucky and southwest West Virginia. Rogersville "high TOC" interval of interest is shown with the red fill.*

<u>Methodology</u>

This evaluation focuses on the wellbore interval that includes the "high TOC" section, an interval where TOC may be as high as ~4 wt%. Well logs from the three wells were analyzed using my proprietary model for reservoir management in oil and gas fields developed in the clay-rich Miocene Monterey Shale of west central California. It uses a modified Waxman-Smits model (see the discussion in Onovughe and Sofolabo, 2016) and a generalized form of the classic Archie equation (Archie, 1952) to calculate clay-bound water in the reservoir, free formation water in reservoir porosity, and total formation water saturation to determine the in-place hydrocarbon volume (Figures 3–5) in the 300 ft evaluation interval. This model efficiently runs in Excel and is part of information available from the project's dataset. Gamma ray logs from the Bruin1 Young and Chesapeake 1 Northup wells were normalized to the mode value of the Bruin 1 Walbridge well to ensure consistency in shale volume calculation (V_{shale}, here used as a proxy for the Rogersville's clay volume) through the interval of interest (Figure 2) completed and tested in these wells. Analysis of produced water from the Rogersville prior to hydraulic fracturing were unavailable, and only one post-treatment sample from the Bruin 1 Young well was analyzed. Formation water resistivity (Rw) measured in this sample was 0.082 Ohms at 77 °F, ~0.03 Ohms at the reservoir temperature of ~180 °F, therefore Rw, 0.025 Ohms, was determined as shown in Onovughe and Sofolabo (2016, Fig. 3) and used in this evaluation. Effective porosity (ϕ_e), total porosity less clay-filled porosity, was calculated as discussed in Bowersox et al. (2019). All three wells were drilled with oil-based drilling mud which risks contamination of conventional whole core, rotary sidewall cores, and drill cutting with oil that could compromise the accuracy of analyses of these materials.

Results

Results of the log analysis of the three Rogersville wells are shown in Figures 3–6 with printed analyses in Appendix 1. An annotated log section, a summary plot of the log analysis with TOC and $So\phi_e$ calculated from core analysis, and mudlog section are shown in Figures 3–5. The log analyses from the Bruin 1 Walbridge and Bruin 1 Young wells show a general agreement with the TOC and core analysis from the wells. In contrast, the patterns of TOC and core analysis values plotted with the log analysis of the Chesapeake LAW 1 Northup (herein "1 Northup") well generally differ from the log analysis and track each other, suggesting possible contamination of the samples by oil from the drilling mud. Estimated equivalent original hydrocarbons in place (oil/gas condensate plus gas), was summarized for each well as original oil in place (OOIP) as barrels of oil per acre (BO/acre): Chesapeake 1 Northup, 5093 BO/acre; Bruin 1 Walbridge, 4735 BO/acre; and Bruin 1 Young, 9736 BO/acre. Average OOIP for the three wells is 6521 BO/acre. Detailed tables of the log analysis from this evaluation are in Appendices 1–3.

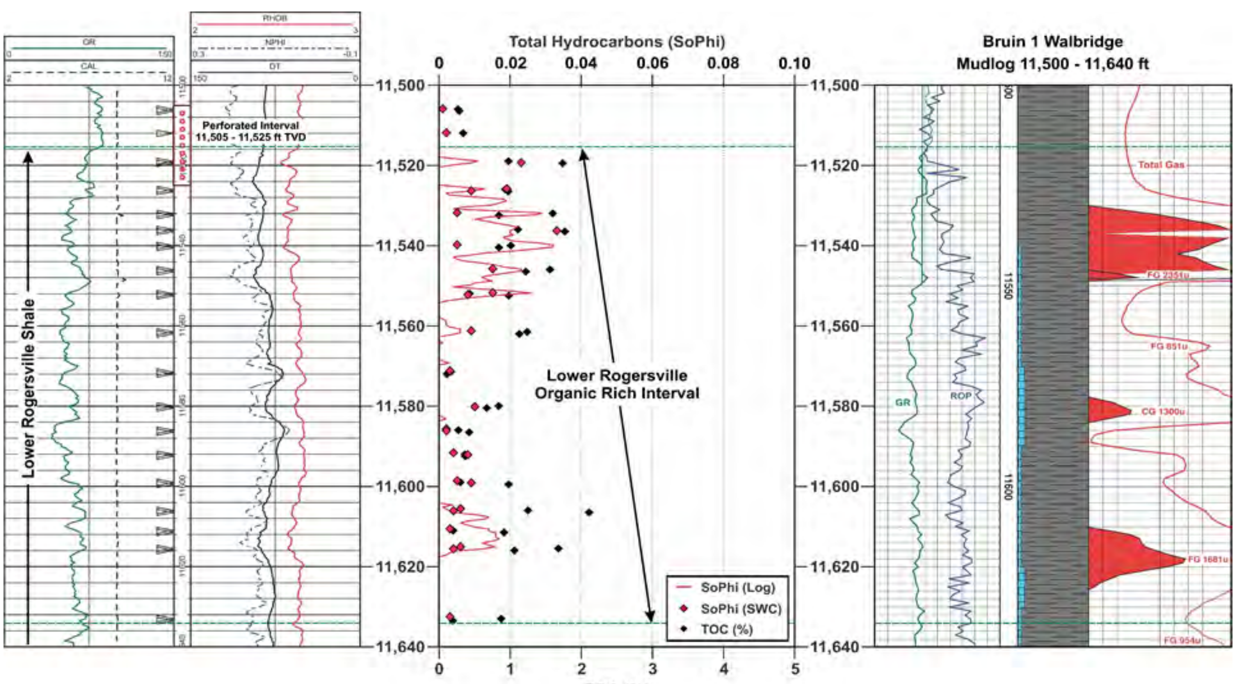


Figure 3. *Montage of logs and log analysis of the Bruin 1 Walbridge well. The core measured* $So\phi_e$ *and upper and lower gas shows on the mudlog generally coincide with higher* $So\phi_e$ *intervals identified by log analysis. Note that the perforated interval of the horizontal wellbore (TVD) lies above the interval identified by core and log analysis.*

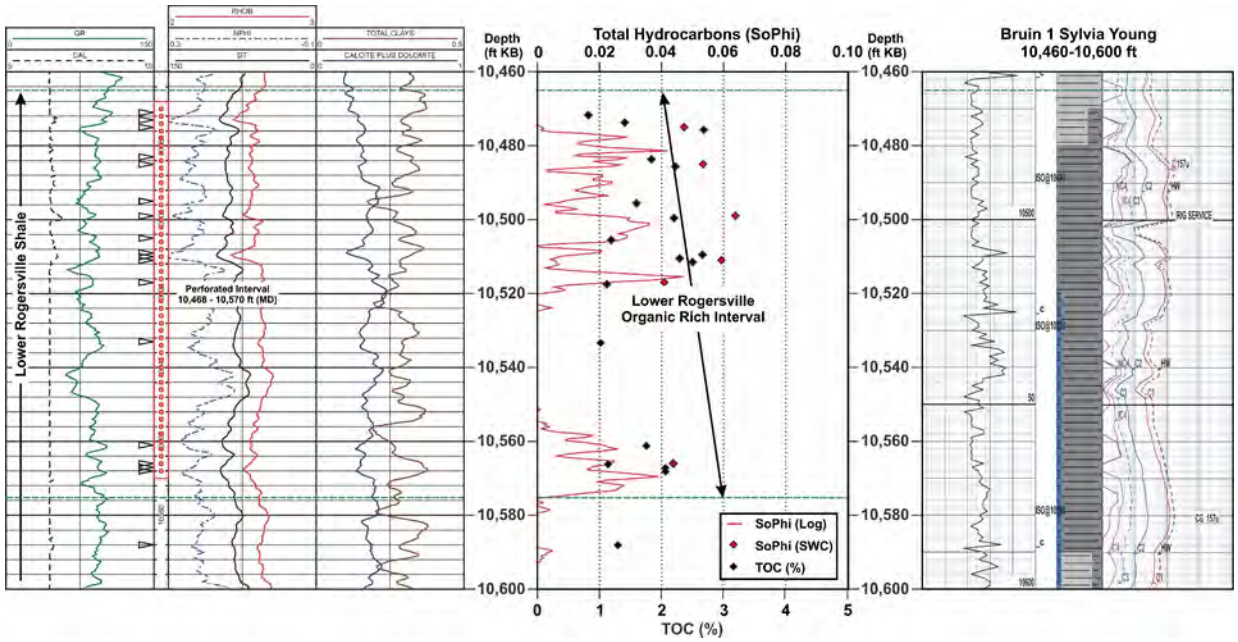


Figure 4. *Montage of logs and log analysis of the Bruin 1 Young well. Again, the core measured Soϕ_e generally coincides with higher Soϕ_e intervals identified by log analysis. The log section on the left plots calculated weight-percent calcite and total clay in the Rogersville organic-rich interval. Higher Soϕ_e in the Rogersville appears to be associated with lower calcite and higher clay content in the upper and lower intervals identified by log analysis, but no obvious relationship appears associated with the middle barren interval. In this well the operator completed the entire interval in the vertical wellbore with shows of hydrocarbons.*

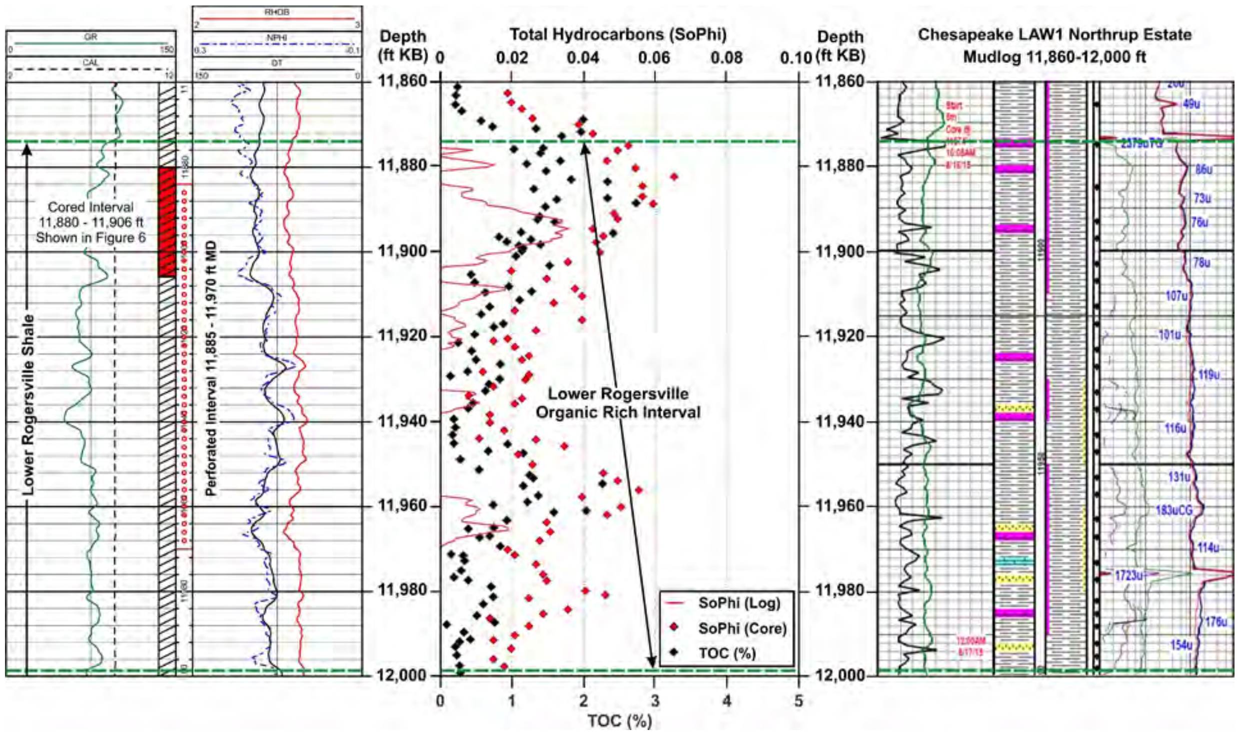


__Figure 5.__ Montage of logs and log analysis of the Chesapeake 1 Northup well. The pattern of TOC values and $So\phi_e$ calculated from analyses of core plugs closely track each other suggesting possible contamination of the analyzed samples by oil-based drilling mud in the wellbore.

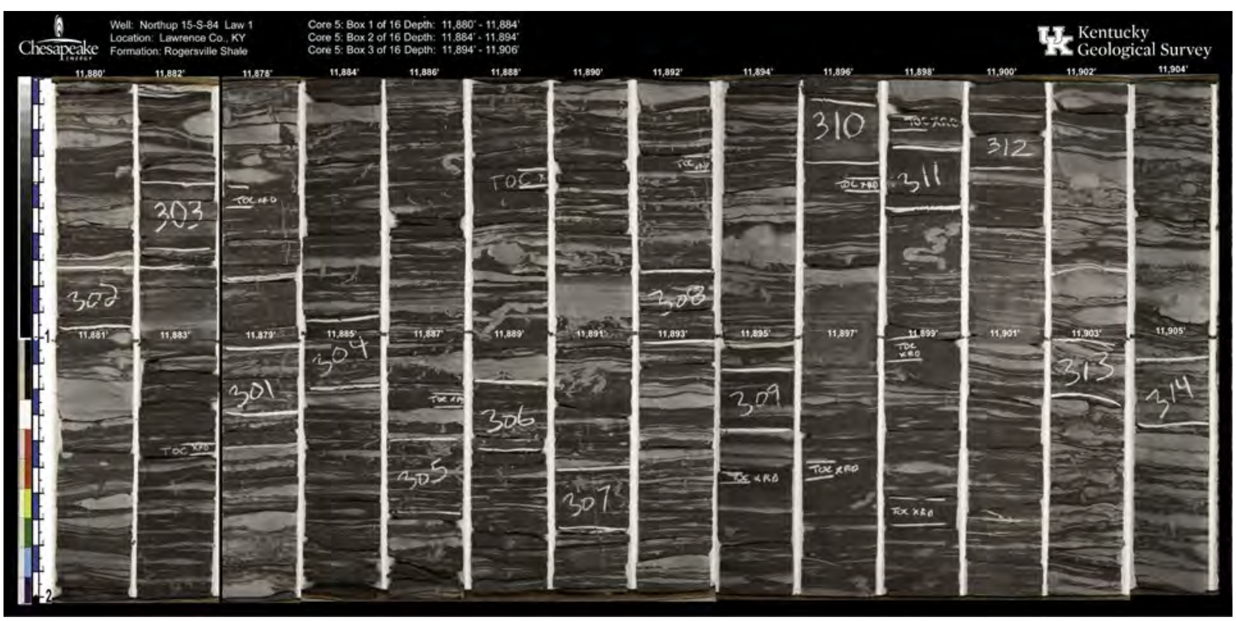


__Figure 6.__ Photos of cores from the section highlighted in Figure 5. Dense dark gray Rogersville Shale is interbedded with gray very fine-grain sandstone/siltstone laminae and sand-filled trace fossils burrows. Little original carbon deposited in this section was preserved as hydrocarbons.

Conclusions

The Cambrian Rogersville Shale was an attractive follow-on play after the extensive oil and gas discoveries in the Devonian Marcellus Shale and Ordovician Utica Shale in the Central and Northern Appalachian Basin in 2003 and 2010 (https://geology.com/articles/utica-shale/). The Rogersville had all of the appearances of another world-class black shale play from shows in earlier wells drilled through the section in the Appalachian Basin. All four wells drilled and tested in the Rogersville proved disappointing, producing gas and gas condensate at non-commercial rates after hydraulic fracturing in both vertical and horizontal wellbores. Log analysis showed low volumes of oil in place, estimated an average 6521 BO/acre in the three wells reviewed here. Photos of cores from the Chesapeake 1 Northup well, showing interbedded dark gray shale and gray very fine-grain sandstone/siltstone in the intervals tested in the prospect wells, suggest little of the carbon that may have been deposited in the section was preserved to generate hydrocarbons. Thus, the Rogersville play has been adequately tested and appears to be non-commercial under the current economic and technological environment.

References

Archie, G. E., 1952, Classification of carbonate reservoir rocks and petrophysical considerations: AAPG Bulletin, vol. 36, p. 218–298.

Bowersox, J.R., Greb, S.F., and Harris, D.C., 2019, Porosity and CO_2 storage capacity of the Maryville–Basal sandstone section (Middle Cambrian), Southern Appalachian Basin, Kentucky: Environmental Geosciences, vol. 26, p. 21–40.

Onovughe, E., and Sofolabo, A., 2016, Saturation modelling: using Waxman-Smits model/equation in saturation determination in dispersed shaly sands: Journal of Multidisciplinary Engineering Science and Technology, vol. 3, p. 4985–4992.

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 1. *Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,500.0	60.40	2.73	4.01	1.59	100.00	36.50	63.50	100.00	0.00	0.00	0.00	0.00
11,500.5	60.30	2.73	4.08	1.62	100.00	36.40	63.60	100.00	0.00	0.00	0.00	0.00
11,501.0	61.90	2.73	4.33	1.65	100.00	38.40	61.60	100.00	0.00	0.00	0.00	0.00
11,501.5	61.30	2.73	4.54	1.76	100.00	37.60	62.40	100.00	0.00	0.00	0.00	0.00
11,502.0	63.40	2.73	5.11	1.87	100.00	40.20	59.80	100.00	0.00	0.00	0.00	0.00
11,502.5	58.60	2.73	5.82	2.41	100.00	34.30	65.70	100.00	0.00	0.00	0.00	0.00
11,503.0	55.20	2.73	5.66	2.53	100.00	30.50	69.50	100.00	0.00	0.00	0.00	0.00
11,503.5	54.20	2.73	5.49	2.51	100.00	29.40	70.60	100.00	0.00	0.00	0.00	0.00
11,504.0	56.40	2.73	4.78	2.08	100.00	31.80	68.20	100.00	0.00	0.00	0.00	0.00
11,504.5	57.90	2.73	4.99	2.10	100.00	33.50	66.50	100.00	0.00	0.00	0.00	0.00
11,505.0	61.70	2.73	4.91	1.88	100.00	38.10	61.90	100.00	0.00	0.00	0.00	0.00
11,505.5	63.10	2.73	5.40	1.99	100.00	39.80	60.20	100.00	0.00	0.00	0.00	0.00
11,506.0	67.00	2.73	5.58	1.84	100.00	44.90	55.10	100.00	0.00	0.00	0.00	0.00
11,506.5	66.40	2.73	6.03	2.03	100.00	44.00	56.00	100.00	0.00	0.00	0.00	0.00
11,507.0	66.70	2.73	5.79	1.93	100.00	44.50	55.50	100.00	0.00	0.00	0.00	0.00
11,507.5	67.10	2.73	5.44	1.79	100.00	45.10	54.90	100.00	0.00	0.00	0.00	0.00
11,508.0	63.60	2.73	4.48	1.63	100.00	40.40	59.60	100.00	0.00	0.00	0.00	0.00
11,508.5	61.60	2.73	3.99	1.53	100.00	38.00	62.00	100.00	0.00	0.00	0.00	0.00
11,509.0	62.00	2.73	3.85	1.46	100.00	38.50	61.50	100.00	0.00	0.00	0.00	0.00
11,509.5	61.30	2.73	3.76	1.45	100.00	37.60	62.40	100.00	0.00	0.00	0.00	0.00
11,510.0	63.60	2.73	3.72	1.35	100.00	40.40	59.60	100.00	0.00	0.00	0.00	0.00
11,510.5	63.60	2.73	4.19	1.53	100.00	40.50	59.50	100.00	0.00	0.00	0.00	0.00
11,511.0	69.00	2.73	5.27	1.64	100.00	47.60	52.40	100.00	0.00	0.00	0.00	0.00
11,511.5	69.20	2.73	6.06	1.87	100.00	47.90	52.10	100.00	0.00	0.00	0.00	0.00
11,512.0	66.60	2.73	6.27	2.09	100.00	44.30	55.70	100.00	0.00	0.00	0.00	0.00
11,512.5	67.10	2.73	6.19	2.04	100.00	45.00	55.00	100.00	0.00	0.00	0.00	0.00
11,513.0	69.20	2.73	6.35	1.96	100.00	47.80	52.20	100.00	0.00	0.00	0.00	0.00
11,513.5	72.40	2.73	6.19	1.71	100.00	52.40	47.60	100.00	0.00	0.00	0.00	0.00
11,514.0	68.30	2.73	5.83	1.85	100.00	46.60	53.40	100.00	0.00	0.00	0.00	0.00
11,514.5	65.70	2.73	5.67	1.95	100.00	43.10	56.90	100.00	0.00	0.00	0.00	0.00
11,515.0	62.00	2.73	5.68	2.16	100.00	38.50	61.50	100.00	0.00	0.00	0.00	0.00
11,515.5	60.60	2.73	5.78	2.28	100.00	36.70	63.30	100.00	0.00	0.00	0.00	0.00
11,516.0	57.70	2.73	6.32	2.67	100.00	33.30	66.70	100.00	0.00	0.00	0.00	0.00
11,516.5	56.50	2.73	7.87	3.42	100.00	32.00	68.00	100.00	0.00	0.00	0.00	0.00
11,517.0	52.20	2.73	8.86	4.24	96.30	27.20	69.10	100.00	0.00	0.00	0.00	0.00
11,517.5	47.10	2.72	8.83	4.67	87.20	22.20	65.00	100.00	0.00	0.00	0.00	0.00
11,518.0	45.20	2.72	8.63	4.73	86.60	20.40	66.20	99.60	0.40	0.00	1.00	0.00
11,518.5	46.60	2.72	9.81	5.24	77.50	21.70	55.80	90.60	9.40	0.01	1.00	0.01
11,519.0	49.90	2.73	11.59	5.81	68.70	24.90	43.80	81.70	18.30	0.01	1.00	0.01
11,519.5	52.20	2.73	11.68	5.59	70.50	27.20	43.30	83.50	16.50	0.01	1.00	0.01
11,520.0	50.90	2.73	10.19	5.00	78.40	25.90	52.50	91.40	8.60	0.00	1.00	0.00
11,520.5	47.60	2.72	7.74	4.06	97.30	22.60	74.60	100.00	0.00	0.00	0.00	0.00
11,521.0	42.80	2.72	6.55	3.75	100.00	18.30	81.70	100.00	0.00	0.00	0.00	0.00
11,521.5	42.10	2.72	5.87	3.40	100.00	17.70	82.30	100.00	0.00	0.00	0.00	0.00
11,522.0	46.00	2.72	6.19	3.34	100.00	21.20	78.80	100.00	0.00	0.00	0.00	0.00
11,522.5	51.00	2.73	6.62	3.24	100.00	26.10	73.90	100.00	0.00	0.00	0.00	0.00
11,523.0	54.40	2.73	7.62	3.48	100.00	29.60	70.40	100.00	0.00	0.00	0.00	0.00
11,523.5	58.00	2.73	8.57	3.60	100.00	33.70	66.30	100.00	0.00	0.00	0.00	0.00
11,524.0	57.90	2.73	8.87	3.74	100.00	33.50	66.50	100.00	0.00	0.00	0.00	0.00
11,524.5	59.20	2.73	8.86	3.61	100.00	35.10	64.90	100.00	0.00	0.00	0.00	0.00
11,525.0	57.10	2.73	8.93	3.83	98.90	32.60	66.30	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 1. *Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,525.5	56.10	2.73	9.55	4.20	72.70	31.40	41.30	85.80	14.20	0.01	1.00	0.01
11,526.0	58.10	2.73	10.14	4.25	56.20	33.80	22.40	69.20	30.80	0.01	1.00	0.01
11,526.5	59.70	2.73	9.68	3.90	64.10	35.60	28.40	77.10	22.90	0.01	1.00	0.01
11,527.0	58.40	2.73	8.13	3.38	80.20	34.10	46.00	93.20	6.80	0.00	1.00	0.00
11,527.5	49.90	2.73	7.13	3.58	78.70	24.90	53.80	91.70	8.30	0.00	1.00	0.00
11,528.0	40.10	2.72	7.26	4.35	65.10	16.10	49.00	78.10	21.90	0.01	1.00	0.01
11,528.5	37.00	2.72	8.35	5.26	53.50	13.70	39.80	66.50	33.50	0.02	1.00	0.02
11,529.0	40.40	2.72	9.23	5.51	52.20	16.30	35.90	65.20	34.80	0.02	1.00	0.02
11,529.5	43.90	2.72	9.09	5.10	53.30	19.30	34.00	66.40	33.60	0.02	1.00	0.02
11,530.0	37.90	2.72	7.50	4.66	54.40	14.40	40.00	67.40	32.60	0.02	1.00	0.02
11,530.5	32.40	2.72	5.47	3.69	67.30	10.50	56.80	80.30	19.70	0.01	1.00	0.01
11,531.0	30.30	2.72	5.38	3.75	77.30	9.20	68.10	90.30	9.70	0.00	1.00	0.00
11,531.5	31.50	2.72	8.18	5.60	55.90	9.90	46.00	68.90	31.10	0.02	1.00	0.02
11,532.0	32.90	2.72	10.63	7.14	46.50	10.80	35.70	59.50	40.50	0.03	1.00	0.03
11,532.5	33.20	2.72	10.65	7.12	48.50	11.00	37.50	61.50	38.50	0.03	1.00	0.03
11,533.0	36.90	2.72	8.91	5.62	61.50	13.60	47.80	74.50	25.50	0.01	1.00	0.01
11,533.5	33.90	2.72	7.54	4.99	67.40	11.50	55.90	80.50	19.50	0.01	1.00	0.01
11,534.0	31.90	2.72	7.58	5.16	62.10	10.20	52.00	75.20	24.80	0.01	1.00	0.01
11,534.5	30.70	2.72	8.03	5.57	57.90	9.40	48.50	70.90	29.10	0.02	1.00	0.02
11,535.0	31.50	2.72	8.62	5.91	54.00	9.90	44.00	67.00	33.00	0.02	1.00	0.02
11,535.5	33.50	2.72	9.09	6.04	51.30	11.20	40.00	64.30	35.70	0.02	1.00	0.02
11,536.0	33.50	2.72	9.04	6.01	51.80	11.20	40.60	64.80	35.20	0.02	1.00	0.02
11,536.5	34.70	2.72	9.00	5.88	52.80	12.00	40.80	65.80	34.20	0.02	1.00	0.02
11,537.0	35.40	2.72	8.89	5.74	52.90	12.50	40.40	66.00	34.00	0.02	1.00	0.02
11,537.5	35.60	2.72	9.12	5.87	51.20	12.70	38.50	64.30	35.70	0.02	1.00	0.02
11,538.0	37.50	2.72	9.07	5.67	54.60	14.00	40.50	67.60	32.40	0.02	1.00	0.02
11,538.5	34.20	2.72	8.91	5.86	55.10	11.70	43.40	68.10	31.90	0.02	1.00	0.02
11,539.0	32.60	2.72	8.94	6.03	52.10	10.60	41.50	65.10	34.90	0.02	1.00	0.02
11,539.5	31.40	2.72	9.67	6.63	44.70	9.80	34.80	57.70	42.30	0.03	1.00	0.03
11,540.0	32.40	2.72	10.26	6.93	41.20	10.50	30.70	54.30	45.70	0.03	1.00	0.03
11,540.5	34.50	2.72	10.54	6.90	39.90	11.90	28.00	53.00	47.00	0.03	1.00	0.03
11,541.0	34.60	2.72	9.45	6.18	42.80	12.00	30.80	55.80	44.20	0.03	1.00	0.03
11,541.5	34.50	2.72	8.09	5.29	47.30	11.90	35.40	60.30	39.70	0.02	1.00	0.02
11,542.0	30.70	2.72	6.43	4.46	57.10	9.40	47.70	70.10	29.90	0.01	1.00	0.01
11,542.5	28.50	2.72	5.42	3.88	63.30	8.10	55.20	76.30	23.70	0.01	1.00	0.01
11,543.0	31.90	2.72	4.82	3.28	74.70	10.20	64.50	87.70	12.30	0.00	1.00	0.00
11,543.5	35.70	2.72	4.99	3.21	70.20	12.70	57.50	83.20	16.80	0.01	1.00	0.01
11,544.0	42.80	2.72	5.56	3.18	64.10	18.40	45.70	77.10	22.90	0.01	1.00	0.01
11,544.5	46.00	2.72	6.43	3.47	51.50	21.10	30.30	64.50	35.50	0.01	1.00	0.01
11,545.0	49.60	2.73	7.36	3.71	43.30	24.60	18.70	56.30	43.70	0.02	1.00	0.02
11,545.5	51.50	2.73	8.02	3.89	39.60	26.60	13.00	52.60	47.40	0.02	1.00	0.02
11,546.0	50.00	2.73	8.24	4.12	31.90	25.00	6.90	44.90	55.10	0.02	1.00	0.02
11,546.5	48.70	2.73	8.08	4.14	32.10	23.70	8.40	45.10	54.90	0.02	1.00	0.02
11,547.0	49.60	2.73	8.09	4.08	39.50	24.60	14.90	52.50	47.50	0.02	1.00	0.02
11,547.5	53.90	2.73	7.91	3.64	45.80	29.10	16.70	58.80	41.20	0.02	1.00	0.02
11,548.0	57.80	2.73	8.05	3.40	51.30	33.40	17.90	64.30	35.70	0.01	1.00	0.01
11,548.5	54.60	2.73	7.71	3.50	51.30	29.80	21.50	64.30	35.70	0.01	1.00	0.01
11,549.0	52.50	2.73	7.89	3.75	48.30	27.60	20.70	61.30	38.70	0.02	1.00	0.02
11,549.5	48.90	2.73	6.86	3.50	58.60	23.90	34.60	71.60	28.40	0.01	1.00	0.01
11,550.0	45.00	2.72	6.34	3.49	61.40	20.30	41.10	74.50	25.50	0.01	1.00	0.01
11,550.5	38.20	2.72	5.80	3.58	76.70	14.60	62.10	89.70	10.30	0.00	1.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 1. *Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,551.0	32.10	2.72	6.12	4.16	57.70	10.30	47.40	70.70	29.30	0.01	1.00	0.01
11,551.5	30.60	2.72	6.70	4.65	43.40	9.40	34.00	56.40	43.60	0.02	1.00	0.02
11,552.0	29.90	2.72	6.89	4.83	34.10	8.90	25.10	47.10	52.90	0.03	1.00	0.03
11,552.5	35.00	2.72	7.00	4.55	47.00	12.20	34.70	60.00	40.00	0.02	1.00	0.02
11,553.0	38.10	2.72	6.78	4.20	60.90	14.50	46.40	73.90	26.10	0.01	1.00	0.01
11,553.5	39.10	2.72	6.80	4.14	73.40	15.30	58.10	86.40	13.60	0.01	1.00	0.01
11,554.0	35.70	2.72	6.16	3.96	82.30	12.80	69.60	95.40	4.60	0.00	1.00	0.00
11,554.5	28.60	2.72	4.87	3.48	94.20	8.20	86.00	100.00	0.00	0.00	0.00	0.00
11,555.0	24.90	2.72	4.26	3.19	100.00	6.20	93.80	100.00	0.00	0.00	0.00	0.00
11,555.5	26.00	2.72	4.59	3.39	93.80	6.80	87.00	100.00	0.00	0.00	0.00	0.00
11,556.0	30.50	2.72	5.17	3.60	88.90	9.30	79.60	100.00	0.00	0.00	0.00	0.00
11,556.5	33.70	2.72	4.73	3.13	100.00	11.40	88.60	100.00	0.00	0.00	0.00	0.00
11,557.0	33.00	2.72	4.43	2.97	100.00	10.90	89.10	100.00	0.00	0.00	0.00	0.00
11,557.5	32.50	2.72	4.35	2.94	100.00	10.60	89.40	100.00	0.00	0.00	0.00	0.00
11,558.0	31.90	2.72	4.62	3.15	93.90	10.20	83.70	100.00	0.00	0.00	0.00	0.00
11,558.5	31.00	2.72	4.40	3.04	83.80	9.60	74.10	96.80	3.20	0.00	1.00	0.00
11,559.0	30.60	2.72	4.25	2.95	79.60	9.40	70.20	92.60	7.40	0.00	1.00	0.00
11,559.5	26.60	2.72	4.15	3.04	79.70	7.10	72.60	92.70	7.30	0.00	1.00	0.00
11,560.0	27.40	2.72	4.31	3.13	80.30	7.50	72.80	93.30	6.70	0.00	1.00	0.00
11,560.5	25.50	2.72	4.16	3.10	76.70	6.50	70.20	89.70	10.30	0.00	1.00	0.00
11,561.0	30.80	2.72	4.67	3.24	67.80	9.50	58.30	80.80	19.20	0.01	1.00	0.01
11,561.5	31.70	2.72	4.97	3.39	69.80	10.10	59.70	82.80	17.20	0.01	1.00	0.01
11,562.0	30.20	2.72	5.09	3.55	69.80	9.10	60.70	82.80	17.20	0.01	1.00	0.01
11,562.5	23.70	2.72	4.37	3.34	77.20	5.60	71.60	90.20	9.80	0.00	1.00	0.00
11,563.0	20.70	2.72	3.90	3.09	90.20	4.30	85.90	100.00	0.00	0.00	0.00	0.00
11,563.5	21.00	2.72	4.19	3.31	92.50	4.40	88.10	100.00	0.00	0.00	0.00	0.00
11,564.0	25.20	2.72	5.11	3.82	89.10	6.30	82.80	100.00	0.00	0.00	0.00	0.00
11,564.5	26.20	2.72	5.76	4.25	84.20	6.90	77.40	97.20	2.80	0.00	1.00	0.00
11,565.0	25.80	2.72	5.46	4.05	86.60	6.60	79.90	99.60	0.40	0.00	1.00	0.00
11,565.5	26.90	2.72	4.84	3.54	95.80	7.20	88.60	100.00	0.00	0.00	0.00	0.00
11,566.0	26.20	2.72	4.12	3.04	100.00	6.90	93.10	100.00	0.00	0.00	0.00	0.00
11,566.5	27.90	2.72	3.95	2.85	100.00	7.80	92.20	100.00	0.00	0.00	0.00	0.00
11,567.0	28.70	2.72	3.84	2.74	100.00	8.20	91.80	100.00	0.00	0.00	0.00	0.00
11,567.5	30.90	2.72	4.08	2.82	100.00	9.60	90.40	100.00	0.00	0.00	0.00	0.00
11,568.0	35.90	2.72	4.64	2.97	100.00	12.90	87.10	100.00	0.00	0.00	0.00	0.00
11,568.5	35.70	2.72	5.41	3.48	91.90	12.80	79.10	100.00	0.00	0.00	0.00	0.00
11,569.0	38.40	2.72	5.97	3.67	84.20	14.80	69.40	97.20	2.80	0.00	1.00	0.00
11,569.5	37.60	2.72	6.08	3.80	79.50	14.10	65.40	92.50	7.50	0.00	1.00	0.00
11,570.0	36.70	2.72	5.65	3.58	86.80	13.50	73.30	99.80	0.20	0.00	1.00	0.00
11,570.5	30.10	2.72	4.93	3.44	91.70	9.10	82.60	100.00	0.00	0.00	0.00	0.00
11,571.0	27.40	2.72	4.27	3.10	100.00	7.50	92.50	100.00	0.00	0.00	0.00	0.00
11,571.5	23.90	2.72	3.62	2.75	100.00	5.70	94.30	100.00	0.00	0.00	0.00	0.00
11,572.0	23.10	2.72	3.31	2.55	100.00	5.30	94.70	100.00	0.00	0.00	0.00	0.00
11,572.5	18.40	2.72	2.79	2.28	100.00	3.40	96.60	100.00	0.00	0.00	0.00	0.00
11,573.0	22.50	2.72	2.47	1.91	100.00	5.10	94.90	100.00	0.00	0.00	0.00	0.00
11,573.5	25.40	2.72	2.36	1.76	100.00	6.50	93.50	100.00	0.00	0.00	0.00	0.00
11,574.0	30.80	2.72	2.78	1.93	100.00	9.50	90.50	100.00	0.00	0.00	0.00	0.00
11,574.5	30.50	2.72	3.60	2.50	100.00	9.30	90.70	100.00	0.00	0.00	0.00	0.00
11,575.0	33.40	2.72	4.50	3.00	100.00	11.10	88.90	100.00	0.00	0.00	0.00	0.00
11,575.5	34.80	2.72	5.40	3.52	100.00	12.10	87.90	100.00	0.00	0.00	0.00	0.00
11,576.0	37.10	2.72	5.96	3.75	98.10	13.70	84.40	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 1. *Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,576.5	39.60	2.72	6.24	3.77	98.30	15.60	82.60	100.00	0.00	0.00	0.00	0.00
11,577.0	40.00	2.72	6.31	3.79	100.00	16.00	84.00	100.00	0.00	0.00	0.00	0.00
11,577.5	39.30	2.72	5.98	3.63	100.00	15.40	84.60	100.00	0.00	0.00	0.00	0.00
11,578.0	37.20	2.72	5.55	3.49	100.00	13.80	86.20	100.00	0.00	0.00	0.00	0.00
11,578.5	35.20	2.72	5.12	3.32	100.00	12.40	87.60	100.00	0.00	0.00	0.00	0.00
11,579.0	37.00	2.72	5.67	3.57	98.90	13.70	85.10	100.00	0.00	0.00	0.00	0.00
11,579.5	36.20	2.72	6.18	3.94	95.70	13.10	82.60	100.00	0.00	0.00	0.00	0.00
11,580.0	39.50	2.72	6.82	4.13	94.10	15.60	78.50	100.00	0.00	0.00	0.00	0.00
11,580.5	39.50	2.72	6.48	3.92	92.80	15.60	77.20	100.00	0.00	0.00	0.00	0.00
11,581.0	41.10	2.72	6.19	3.64	97.00	16.90	80.00	100.00	0.00	0.00	0.00	0.00
11,581.5	40.10	2.72	6.09	3.65	99.60	16.10	83.60	100.00	0.00	0.00	0.00	0.00
11,582.0	39.70	2.72	5.91	3.57	100.00	15.70	84.30	100.00	0.00	0.00	0.00	0.00
11,582.5	34.20	2.72	5.30	3.49	90.40	11.70	78.80	100.00	0.00	0.00	0.00	0.00
11,583.0	28.80	2.72	4.25	3.03	82.30	8.30	74.10	95.30	4.70	0.00	1.00	0.00
11,583.5	20.20	2.72	3.46	2.76	80.20	4.10	76.10	93.20	6.80	0.00	1.00	0.00
11,584.0	16.60	2.72	3.04	2.53	86.40	2.70	83.70	99.50	0.50	0.00	1.00	0.00
11,584.5	14.40	2.71	3.08	2.63	91.90	2.10	89.80	100.00	0.00	0.00	0.00	0.00
11,585.0	12.30	2.71	3.14	2.75	94.70	1.50	93.20	100.00	0.00	0.00	0.00	0.00
11,585.5	9.50	2.71	3.01	2.72	88.20	0.90	87.30	100.00	0.00	0.00	0.00	0.00
11,586.0	6.00	2.71	2.80	2.63	93.80	0.40	93.50	100.00	0.00	0.00	0.00	0.00
11,586.5	10.60	2.71	2.62	2.35	100.00	1.10	98.90	100.00	0.00	0.00	0.00	0.00
11,587.0	14.80	2.71	2.75	2.34	100.00	2.20	97.80	100.00	0.00	0.00	0.00	0.00
11,587.5	22.20	2.72	2.86	2.23	100.00	4.90	95.10	100.00	0.00	0.00	0.00	0.00
11,588.0	26.40	2.72	3.40	2.50	100.00	7.00	93.00	100.00	0.00	0.00	0.00	0.00
11,588.5	34.30	2.72	4.13	2.72	100.00	11.80	88.20	100.00	0.00	0.00	0.00	0.00
11,589.0	33.90	2.72	4.79	3.16	100.00	11.50	88.50	100.00	0.00	0.00	0.00	0.00
11,589.5	35.70	2.72	4.79	3.08	100.00	12.70	87.30	100.00	0.00	0.00	0.00	0.00
11,590.0	32.70	2.72	4.07	2.74	100.00	10.70	89.30	100.00	0.00	0.00	0.00	0.00
11,590.5	33.80	2.72	3.30	2.19	100.00	11.40	88.60	100.00	0.00	0.00	0.00	0.00
11,591.0	30.70	2.72	2.72	1.88	100.00	9.40	90.60	100.00	0.00	0.00	0.00	0.00
11,591.5	30.50	2.72	2.95	2.05	100.00	9.30	90.70	100.00	0.00	0.00	0.00	0.00
11,592.0	28.00	2.72	3.15	2.27	100.00	7.80	92.20	100.00	0.00	0.00	0.00	0.00
11,592.5	31.50	2.72	2.98	2.04	100.00	9.90	90.10	100.00	0.00	0.00	0.00	0.00
11,593.0	31.50	2.72	3.00	2.05	100.00	9.90	90.10	100.00	0.00	0.00	0.00	0.00
11,593.5	32.40	2.72	2.92	1.98	100.00	10.50	89.50	100.00	0.00	0.00	0.00	0.00
11,594.0	27.80	2.72	2.97	2.14	100.00	7.70	92.30	100.00	0.00	0.00	0.00	0.00
11,594.5	27.40	2.72	2.79	2.03	100.00	7.50	92.50	100.00	0.00	0.00	0.00	0.00
11,595.0	33.20	2.72	2.81	1.88	100.00	11.00	89.00	100.00	0.00	0.00	0.00	0.00
11,595.5	34.30	2.72	3.17	2.08	100.00	11.80	88.20	100.00	0.00	0.00	0.00	0.00
11,596.0	34.70	2.72	3.11	2.03	100.00	12.10	87.90	100.00	0.00	0.00	0.00	0.00
11,596.5	29.50	2.72	2.37	1.67	100.00	8.70	91.30	100.00	0.00	0.00	0.00	0.00
11,597.0	29.60	2.72	2.44	1.71	100.00	8.80	91.20	100.00	0.00	0.00	0.00	0.00
11,597.5	30.40	2.72	2.92	2.03	100.00	9.20	90.80	100.00	0.00	0.00	0.00	0.00
11,598.0	38.40	2.72	4.15	2.56	100.00	14.70	85.30	100.00	0.00	0.00	0.00	0.00
11,598.5	44.10	2.72	4.55	2.55	100.00	19.50	80.50	100.00	0.00	0.00	0.00	0.00
11,599.0	45.40	2.72	5.08	2.77	100.00	20.60	79.40	100.00	0.00	0.00	0.00	0.00
11,599.5	41.40	2.72	5.13	3.01	100.00	17.10	82.90	100.00	0.00	0.00	0.00	0.00
11,600.0	40.40	2.72	4.95	2.95	100.00	16.30	83.70	100.00	0.00	0.00	0.00	0.00
11,600.5	42.00	2.72	4.48	2.60	100.00	17.70	82.30	100.00	0.00	0.00	0.00	0.00
11,601.0	43.90	2.72	4.60	2.58	100.00	19.20	80.80	100.00	0.00	0.00	0.00	0.00
11,601.5	41.10	2.72	4.68	2.75	100.00	16.90	83.10	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 1. *Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,602.0	41.20	2.72	5.09	2.99	100.00	17.00	83.00	100.00	0.00	0.00	0.00	0.00
11,602.5	39.40	2.72	5.09	3.09	100.00	15.50	84.50	100.00	0.00	0.00	0.00	0.00
11,603.0	37.20	2.72	4.96	3.11	100.00	13.90	86.10	100.00	0.00	0.00	0.00	0.00
11,603.5	34.90	2.72	4.73	3.08	100.00	12.20	87.80	100.00	0.00	0.00	0.00	0.00
11,604.0	31.20	2.72	5.18	3.56	100.00	9.70	90.30	100.00	0.00	0.00	0.00	0.00
11,604.5	35.10	2.72	6.32	4.11	87.90	12.30	75.50	100.00	0.00	0.00	0.00	0.00
11,605.0	36.50	2.72	7.16	4.54	79.00	13.30	65.70	92.00	8.00	0.00	1.00	0.00
11,605.5	40.70	2.72	7.18	4.25	83.80	16.60	67.20	96.80	3.20	0.00	1.00	0.00
11,606.0	44.20	2.72	7.61	4.25	82.20	19.50	62.70	95.20	4.80	0.00	1.00	0.00
11,606.5	45.60	2.72	7.68	4.18	80.80	20.80	60.00	93.80	6.20	0.00	1.00	0.00
11,607.0	45.30	2.72	7.80	4.27	74.70	20.50	54.20	87.70	12.30	0.01	1.00	0.01
11,607.5	34.50	2.72	7.16	4.69	63.90	11.90	51.90	76.90	23.10	0.01	1.00	0.01
11,608.0	27.30	2.72	6.55	4.76	58.30	7.40	50.90	71.30	28.70	0.01	1.00	0.01
11,608.5	26.70	2.72	6.13	4.49	57.90	7.10	50.80	70.90	29.10	0.01	1.00	0.01
11,609.0	33.90	2.72	5.76	3.80	66.70	11.50	55.20	79.70	20.30	0.01	1.00	0.01
11,609.5	41.70	2.72	6.26	3.65	70.20	17.40	52.80	83.30	16.70	0.01	1.00	0.01
11,610.0	41.50	2.72	6.73	3.93	66.10	17.30	48.80	79.10	20.90	0.01	1.00	0.01
11,610.5	41.70	2.72	7.17	4.18	62.20	17.40	44.90	75.20	24.80	0.01	1.00	0.01
11,611.0	42.10	2.72	7.96	4.61	57.60	17.70	39.90	70.60	29.40	0.01	1.00	0.01
11,611.5	47.60	2.72	8.94	4.69	56.70	22.60	34.10	69.80	30.20	0.01	1.00	0.01
11,612.0	49.10	2.73	9.42	4.79	53.90	24.20	29.80	66.90	33.10	0.02	1.00	0.02
11,612.5	46.70	2.72	8.74	4.66	52.90	21.80	31.20	66.00	34.00	0.02	1.00	0.02
11,613.0	41.40	2.72	7.77	4.56	52.10	17.10	35.00	65.10	34.90	0.02	1.00	0.02
11,613.5	42.30	2.72	7.77	4.48	49.00	17.90	31.00	62.00	38.00	0.02	1.00	0.02
11,614.0	47.90	2.72	7.91	4.12	51.70	22.90	28.80	64.70	35.30	0.02	1.00	0.02
11,614.5	51.20	2.73	8.13	3.97	55.50	26.20	29.30	68.60	31.40	0.01	1.00	0.01
11,615.0	51.80	2.73	8.95	4.32	53.80	26.80	27.00	66.80	33.20	0.01	1.00	0.01
11,615.5	47.90	2.72	9.04	4.71	52.40	22.90	29.50	65.40	34.60	0.02	1.00	0.02
11,616.0	46.60	2.72	8.27	4.42	59.10	21.70	37.40	72.10	27.90	0.01	1.00	0.01
11,616.5	44.90	2.72	6.84	3.77	73.10	20.10	52.90	86.10	13.90	0.01	1.00	0.01
11,617.0	45.70	2.72	6.65	3.61	80.00	20.90	59.10	93.00	7.00	0.00	1.00	0.00
11,617.5	47.20	2.72	6.95	3.67	81.10	22.30	58.80	94.10	5.90	0.00	1.00	0.00
11,618.0	43.50	2.72	6.26	3.54	86.70	18.90	67.80	99.70	0.30	0.00	1.00	0.00
11,618.5	38.90	2.72	4.92	3.01	100.00	15.10	84.90	100.00	0.00	0.00	0.00	0.00
11,619.0	36.00	2.72	3.83	2.45	100.00	13.00	87.00	100.00	0.00	0.00	0.00	0.00
11,619.5	41.10	2.72	3.52	2.07	100.00	16.90	83.10	100.00	0.00	0.00	0.00	0.00
11,620.0	42.90	2.72	3.65	2.09	100.00	18.40	81.60	100.00	0.00	0.00	0.00	0.00
11,620.5	41.60	2.72	4.41	2.57	100.00	17.30	82.70	100.00	0.00	0.00	0.00	0.00
11,621.0	33.40	2.72	4.76	3.17	100.00	11.20	88.80	100.00	0.00	0.00	0.00	0.00
11,621.5	34.50	2.72	4.73	3.10	100.00	11.90	88.10	100.00	0.00	0.00	0.00	0.00
11,622.0	35.90	2.72	4.48	2.87	100.00	12.90	87.10	100.00	0.00	0.00	0.00	0.00
11,622.5	41.40	2.72	4.72	2.77	100.00	17.10	82.90	100.00	0.00	0.00	0.00	0.00
11,623.0	37.70	2.72	5.01	3.12	100.00	14.20	85.80	100.00	0.00	0.00	0.00	0.00
11,623.5	36.90	2.72	4.96	3.13	100.00	13.60	86.40	100.00	0.00	0.00	0.00	0.00
11,624.0	38.70	2.72	4.72	2.89	100.00	15.00	85.00	100.00	0.00	0.00	0.00	0.00
11,624.5	41.70	2.72	4.60	2.68	100.00	17.40	82.60	100.00	0.00	0.00	0.00	0.00
11,625.0	41.60	2.72	4.50	2.63	100.00	17.30	82.70	100.00	0.00	0.00	0.00	0.00
11,625.5	42.30	2.72	4.97	2.87	100.00	17.90	82.10	100.00	0.00	0.00	0.00	0.00
11,626.0	43.50	2.72	5.17	2.92	100.00	18.90	81.10	100.00	0.00	0.00	0.00	0.00
11,626.5	44.40	2.72	5.49	3.05	100.00	19.70	80.30	100.00	0.00	0.00	0.00	0.00
11,627.0	39.90	2.72	5.24	3.15	100.00	16.00	84.00	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

***Appendix 1.** Log Analysis of the Bruin 1 Walbridge Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11,627.5	38.10	2.72	5.45	3.37	100.00	14.50	85.50	100.00	0.00	0.00	0.00	0.00
11,628.0	38.80	2.72	5.21	3.19	100.00	15.10	84.90	100.00	0.00	0.00	0.00	0.00
11,628.5	44.70	2.72	4.77	2.64	100.00	20.00	80.00	100.00	0.00	0.00	0.00	0.00
11,629.0	40.70	2.72	4.22	2.51	100.00	16.50	83.50	100.00	0.00	0.00	0.00	0.00
11,629.5	42.60	2.72	4.39	2.52	100.00	18.20	81.80	100.00	0.00	0.00	0.00	0.00
11,630.0	42.70	2.72	5.01	2.87	100.00	18.30	81.70	100.00	0.00	0.00	0.00	0.00
11,630.5	52.00	2.73	5.67	2.72	100.00	27.00	73.00	100.00	0.00	0.00	0.00	0.00
11,631.0	54.70	2.73	5.55	2.51	100.00	30.00	70.00	100.00	0.00	0.00	0.00	0.00
11,631.5	51.50	2.73	5.04	2.44	100.00	26.50	73.50	100.00	0.00	0.00	0.00	0.00
11,632.0	45.70	2.72	4.77	2.59	100.00	20.80	79.20	100.00	0.00	0.00	0.00	0.00
11,632.5	43.50	2.72	4.90	2.77	100.00	18.90	81.10	100.00	0.00	0.00	0.00	0.00
11,633.0	42.10	2.72	5.30	3.07	100.00	17.70	82.30	100.00	0.00	0.00	0.00	0.00
11,633.5	44.30	2.72	5.79	3.23	100.00	19.60	80.40	100.00	0.00	0.00	0.00	0.00
11,634.0	46.90	2.72	7.14	3.79	100.00	22.00	78.00	100.00	0.00	0.00	0.00	0.00
11,634.5	50.20	2.73	7.29	3.63	100.00	25.20	74.80	100.00	0.00	0.00	0.00	0.00
11,635.0	50.10	2.73	6.25	3.12	100.00	25.10	74.90	100.00	0.00	0.00	0.00	0.00
11,635.5	48.30	2.72	4.45	2.30	100.00	23.40	76.60	100.00	0.00	0.00	0.00	0.00
11,636.0	44.30	2.72	3.75	2.09	100.00	19.60	80.40	100.00	0.00	0.00	0.00	0.00
11,636.5	42.30	2.72	3.82	2.20	100.00	17.90	82.10	100.00	0.00	0.00	0.00	0.00
11,637.0	36.30	2.72	4.10	2.61	100.00	13.20	86.80	100.00	0.00	0.00	0.00	0.00
11,637.5	35.30	2.72	3.70	2.40	100.00	12.50	87.50	100.00	0.00	0.00	0.00	0.00
11,638.0	36.70	2.72	3.80	2.40	100.00	13.50	86.50	100.00	0.00	0.00	0.00	0.00
11,638.5	37.50	2.72	3.70	2.31	100.00	14.10	85.90	100.00	0.00	0.00	0.00	0.00
11,639.0	37.80	2.72	4.22	2.62	100.00	14.30	85.70	100.00	0.00	0.00	0.00	0.00
11,639.5	36.20	2.72	4.55	2.90	100.00	13.10	86.90	100.00	0.00	0.00	0.00	0.00
11,640.0	38.10	2.72	4.97	3.08	100.00	14.60	85.40	100.00	0.00	0.00	0.00	0.00
11,640.5	40.50	2.72	5.44	3.24	100.00	16.40	83.60	100.00	0.00	0.00	0.00	0.00
11,641.0	44.70	2.72	5.35	2.96	100.00	19.90	80.10	100.00	0.00	0.00	0.00	0.00
11,641.5	42.70	2.72	5.04	2.88	100.00	18.30	81.70	100.00	0.00	0.00	0.00	0.00
11,642.0	43.50	2.72	4.69	2.65	100.00	18.90	81.10	100.00	0.00	0.00	0.00	0.00
11,642.5	43.40	2.72	4.82	2.73	100.00	18.90	81.10	100.00	0.00	0.00	0.00	0.00
11,643.0	50.00	2.73	4.78	2.39	100.00	25.00	75.00	100.00	0.00	0.00	0.00	0.00
11,643.5	50.00	2.73	4.64	2.32	100.00	25.00	75.00	100.00	0.00	0.00	0.00	0.00
11,644.0	50.90	2.73	4.45	2.19	100.00	25.90	74.10	100.00	0.00	0.00	0.00	0.00
11,644.5	49.20	2.73	4.48	2.28	100.00	24.20	75.80	100.00	0.00	0.00	0.00	0.00
11,645.0	47.00	2.72	4.37	2.32	100.00	22.10	77.90	100.00	0.00	0.00	0.00	0.00
11,645.5	39.40	2.72	4.10	2.48	100.00	15.50	84.50	100.00	0.00	0.00	0.00	0.00
11,646.0	37.90	2.72	3.86	2.40	100.00	14.40	85.60	100.00	0.00	0.00	0.00	0.00
11,646.5	40.00	2.72	3.73	2.24	100.00	16.00	84.00	100.00	0.00	0.00	0.00	0.00
11,647.0	42.20	2.72	3.37	1.95	100.00	17.80	82.20	100.00	0.00	0.00	0.00	0.00
11,647.5	34.30	2.72	2.72	1.79	100.00	11.80	88.20	100.00	0.00	0.00	0.00	0.00
11,648.0	28.70	2.72	1.84	1.31	100.00	8.20	91.80	100.00	0.00	0.00	0.00	0.00
11,648.5	30.30	2.72	2.30	1.60	100.00	9.20	90.80	100.00	0.00	0.00	0.00	0.00
11,649.0	33.80	2.72	2.48	1.64	100.00	11.40	88.60	100.00	0.00	0.00	0.00	0.00
11,649.5	37.00	2.72	3.22	2.03	100.00	13.70	86.30	100.00	0.00	0.00	0.00	0.00
11,650.0	40.00	2.72	3.50	2.10	100.00	16.00	84.00	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

***Appendix 2.** Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10450.0	53.00	2.73	5.28	2.48	100.00	28.10	71.90	100.00	0.00	0.00	0.00	0.00
10450.5	55.10	2.73	5.20	2.34	100.00	30.40	69.60	100.00	0.00	0.00	0.00	0.00
10451.0	59.20	2.73	4.70	1.92	100.00	35.00	65.00	100.00	0.00	0.00	0.00	0.00
10451.5	69.30	2.73	4.67	1.43	100.00	48.00	52.00	100.00	0.00	0.00	0.00	0.00
10452.0	77.30	2.74	5.09	1.15	100.00	59.80	40.20	100.00	0.00	0.00	0.00	0.00
10452.5	81.40	2.74	5.67	1.05	100.00	100.00	0.00	100.00	0.00	0.00	0.00	0.00
10453.0	73.50	2.73	5.86	1.55	100.00	54.10	45.90	100.00	0.00	0.00	0.00	0.00
10453.5	64.00	2.73	5.67	2.04	100.00	41.00	59.00	100.00	0.00	0.00	0.00	0.00
10454.0	62.40	2.73	5.08	1.91	100.00	38.90	61.10	100.00	0.00	0.00	0.00	0.00
10454.5	64.00	2.73	4.86	1.75	100.00	41.00	59.00	100.00	0.00	0.00	0.00	0.00
10455.0	62.90	2.73	4.86	1.80	100.00	39.50	60.50	100.00	0.00	0.00	0.00	0.00
10455.5	59.10	2.73	5.45	2.23	100.00	34.90	65.10	100.00	0.00	0.00	0.00	0.00
10456.0	61.20	2.73	5.98	2.32	100.00	37.40	62.60	100.00	0.00	0.00	0.00	0.00
10456.5	65.00	2.73	6.13	2.15	100.00	42.20	57.80	100.00	0.00	0.00	0.00	0.00
10457.0	65.20	2.73	6.00	2.09	100.00	42.60	57.40	100.00	0.00	0.00	0.00	0.00
10457.5	62.70	2.73	5.69	2.12	100.00	39.30	60.70	100.00	0.00	0.00	0.00	0.00
10458.0	58.50	2.73	5.56	2.31	100.00	34.20	65.80	100.00	0.00	0.00	0.00	0.00
10458.5	58.90	2.73	5.53	2.28	100.00	34.70	65.30	100.00	0.00	0.00	0.00	0.00
10459.0	57.20	2.73	5.28	2.26	100.00	32.70	67.30	100.00	0.00	0.00	0.00	0.00
10459.5	54.10	2.73	4.99	2.29	100.00	29.30	70.70	100.00	0.00	0.00	0.00	0.00
10460.0	53.00	2.73	4.86	2.29	100.00	28.10	71.90	100.00	0.00	0.00	0.00	0.00
10460.5	58.10	2.73	4.94	2.07	100.00	33.70	66.30	100.00	0.00	0.00	0.00	0.00
10461.0	68.20	2.73	4.99	1.59	100.00	46.50	53.50	100.00	0.00	0.00	0.00	0.00
10461.5	75.70	2.73	5.22	1.27	100.00	57.30	42.70	100.00	0.00	0.00	0.00	0.00
10462.0	73.80	2.73	5.10	1.34	100.00	54.50	45.50	100.00	0.00	0.00	0.00	0.00
10462.5	68.90	2.73	4.83	1.50	100.00	47.40	52.60	100.00	0.00	0.00	0.00	0.00
10463.0	68.20	2.73	4.46	1.42	100.00	46.50	53.50	100.00	0.00	0.00	0.00	0.00
10463.5	67.20	2.73	4.55	1.49	100.00	45.20	54.80	100.00	0.00	0.00	0.00	0.00
10464.0	62.40	2.73	5.05	1.90	100.00	38.90	61.10	100.00	0.00	0.00	0.00	0.00
10464.5	59.70	2.73	5.51	2.22	100.00	35.60	64.40	100.00	0.00	0.00	0.00	0.00
10465.0	59.40	2.73	6.38	2.59	100.00	35.30	64.70	100.00	0.00	0.00	0.00	0.00
10465.5	57.80	2.73	7.55	3.18	100.00	33.40	66.60	100.00	0.00	0.00	0.00	0.00
10466.0	55.00	2.73	8.74	3.94	84.20	30.20	54.00	97.30	2.70	0.00	0.50	0.00
10466.5	56.50	2.73	9.02	3.93	81.40	31.90	49.50	94.40	5.60	0.00	0.50	0.00
10467.0	56.60	2.73	8.53	3.70	84.70	32.00	52.70	97.70	2.30	0.00	0.50	0.00
10467.5	50.90	2.73	8.06	3.96	78.00	25.90	52.10	91.00	9.00	0.00	0.50	0.00
10468.0	45.30	2.72	9.59	5.24	56.90	20.50	36.40	70.00	30.00	0.02	0.50	0.01
10468.5	47.20	2.73	10.84	5.73	51.10	22.30	28.80	64.10	35.90	0.02	0.50	0.01
10469.0	44.20	2.72	12.12	6.76	43.80	19.60	24.20	56.80	43.20	0.03	0.50	0.02
10469.5	42.90	2.72	11.19	6.40	48.00	18.40	29.60	61.00	39.00	0.03	0.50	0.01
10470.0	49.80	2.73	11.35	5.70	55.70	24.80	30.90	68.70	31.30	0.02	0.50	0.01
10470.5	57.40	2.73	12.21	5.20	61.80	32.90	28.80	74.80	25.20	0.01	0.50	0.01
10471.0	64.40	2.73	14.53	5.17	61.70	41.50	20.10	74.70	25.30	0.01	0.50	0.01
10471.5	62.80	2.73	15.39	5.72	56.80	39.50	17.30	69.80	30.20	0.02	0.50	0.01
10472.0	59.50	2.73	15.51	6.27	51.30	35.50	15.90	64.40	35.60	0.02	0.50	0.01
10472.5	55.50	2.73	16.66	7.42	42.20	30.80	11.40	55.20	44.80	0.03	0.50	0.02
10473.0	52.30	2.73	17.49	8.35	36.50	27.30	9.20	49.50	50.50	0.04	0.50	0.02
10473.5	57.70	2.73	14.86	6.29	48.50	33.30	15.20	61.50	38.50	0.02	0.50	0.01
10474.0	52.30	2.73	10.37	4.95	60.90	27.30	33.60	73.90	26.10	0.01	0.50	0.01
10474.5	43.10	2.72	7.92	4.51	60.30	18.60	41.70	73.30	26.70	0.01	0.50	0.01
10475.0	28.60	2.72	8.19	5.85	38.00	8.20	29.80	51.00	49.00	0.03	0.50	0.01

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 2. *Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10475.5	27.50	2.72	7.63	5.53	40.40	7.60	32.80	53.40	46.60	0.03	0.50	0.01
10476.0	29.60	2.72	7.04	4.95	50.60	8.80	41.80	63.60	36.40	0.02	0.50	0.01
10476.5	33.30	2.72	8.21	5.47	49.30	11.10	38.20	62.30	37.70	0.02	0.50	0.01
10477.0	36.10	2.72	9.93	6.34	44.10	13.00	31.00	57.10	42.90	0.03	0.50	0.01
10477.5	43.30	2.72	10.33	5.86	46.40	18.70	27.60	59.40	40.60	0.02	0.50	0.01
10478.0	48.70	2.73	8.70	4.46	60.10	23.70	36.40	73.10	26.90	0.01	0.50	0.01
10478.5	48.40	2.73	6.90	3.56	78.20	23.40	54.80	91.20	8.80	0.00	0.50	0.00
10479.0	46.40	2.73	6.74	3.61	78.10	21.50	56.60	91.10	8.90	0.00	0.50	0.00
10479.5	45.60	2.72	8.46	4.60	59.00	20.80	38.30	72.10	27.90	0.01	0.50	0.01
10480.0	47.60	2.73	10.12	5.30	47.90	22.70	25.20	60.90	39.10	0.02	0.50	0.01
10480.5	47.90	2.73	10.24	5.34	47.80	22.90	24.90	60.90	39.10	0.02	0.50	0.01
10481.0	45.90	2.73	9.34	5.05	51.60	21.10	30.50	64.60	35.40	0.02	0.50	0.01
10481.5	46.40	2.73	9.68	5.19	51.60	21.60	30.10	64.60	35.40	0.02	0.50	0.01
10482.0	45.10	2.72	10.69	5.87	46.60	20.30	26.30	59.60	40.40	0.02	0.50	0.01
10482.5	45.00	2.72	10.68	5.88	45.80	20.20	25.60	58.80	41.20	0.02	0.50	0.01
10483.0	45.90	2.73	10.03	5.42	50.50	21.10	29.40	63.50	36.50	0.02	0.50	0.01
10483.5	49.50	2.73	9.76	4.93	54.90	24.50	30.30	67.90	32.10	0.02	0.50	0.01
10484.0	50.40	2.73	9.86	4.89	58.90	25.40	33.50	71.90	28.10	0.01	0.50	0.01
10484.5	51.00	2.73	9.92	4.86	63.10	26.00	37.10	76.10	23.90	0.01	0.50	0.01
10485.0	47.00	2.73	10.14	5.37	59.10	22.10	36.90	72.10	27.90	0.02	0.50	0.01
10485.5	46.70	2.73	10.74	5.73	55.70	21.80	33.90	68.70	31.30	0.02	0.50	0.01
10486.0	43.40	2.72	11.19	6.34	50.40	18.80	31.60	63.40	36.60	0.02	0.50	0.01
10486.5	46.30	2.73	10.68	5.73	55.40	21.50	33.90	68.40	31.60	0.02	0.50	0.01
10487.0	48.30	2.73	9.85	5.09	62.50	23.30	39.20	75.50	24.50	0.01	0.50	0.01
10487.5	48.90	2.73	9.28	4.74	68.30	23.90	44.30	81.30	18.70	0.01	0.50	0.00
10488.0	48.10	2.73	8.83	4.59	72.40	23.10	49.30	85.40	14.60	0.01	0.50	0.00
10488.5	52.10	2.73	8.70	4.16	81.30	27.20	54.20	94.40	5.60	0.00	0.50	0.00
10489.0	50.90	2.73	9.09	4.47	73.80	25.90	47.90	86.80	13.20	0.01	0.50	0.00
10489.5	43.60	2.72	8.63	4.87	65.30	19.00	46.30	78.40	21.60	0.01	0.50	0.01
10490.0	36.30	2.72	7.84	4.99	61.70	13.20	48.50	74.70	25.30	0.01	0.50	0.01
10490.5	35.80	2.72	6.71	4.31	72.40	12.80	59.60	85.40	14.60	0.01	0.50	0.00
10491.0	40.30	2.72	7.19	4.29	72.90	16.30	56.60	85.90	14.10	0.01	0.50	0.00
10491.5	38.10	2.72	8.17	5.06	58.00	14.50	43.50	71.00	29.00	0.02	0.50	0.01
10492.0	35.80	2.72	9.20	5.91	46.10	12.80	33.30	59.20	40.80	0.02	0.50	0.01
10492.5	31.90	2.72	9.59	6.52	41.40	10.20	31.20	54.40	45.60	0.03	0.50	0.02
10493.0	33.30	2.72	9.62	6.42	42.30	11.10	31.30	55.40	44.60	0.03	0.50	0.01
10493.5	30.70	2.72	9.33	6.47	40.10	9.40	30.70	53.10	46.90	0.03	0.50	0.02
10494.0	29.80	2.72	9.82	6.90	35.20	8.90	26.30	48.20	51.80	0.04	0.50	0.02
10494.5	24.90	2.72	9.69	7.27	37.40	6.20	31.20	50.40	49.60	0.04	0.50	0.02
10495.0	27.90	2.72	10.17	7.33	41.10	7.80	33.30	54.10	45.90	0.03	0.50	0.02
10495.5	23.80	2.72	9.74	7.43	43.40	5.70	37.70	56.40	43.60	0.03	0.50	0.02
10496.0	29.60	2.72	10.33	7.27	45.50	8.80	36.70	58.50	41.50	0.03	0.50	0.02
10496.5	30.60	2.72	10.47	7.27	46.50	9.40	37.20	59.50	40.50	0.03	0.50	0.02
10497.0	35.20	2.72	10.71	6.94	49.30	12.40	36.90	62.30	37.70	0.03	0.50	0.01
10497.5	36.70	2.72	11.46	7.26	47.40	13.50	34.00	60.40	39.60	0.03	0.50	0.01
10498.0	37.40	2.72	11.76	7.36	47.40	14.00	33.40	60.40	39.60	0.03	0.50	0.02
10498.5	45.70	2.73	13.30	7.22	48.10	20.90	27.20	61.10	38.90	0.03	0.50	0.01
10499.0	44.00	2.72	12.59	7.05	49.80	19.30	30.40	62.80	37.20	0.03	0.50	0.01
10499.5	40.40	2.72	10.75	6.41	54.00	16.30	37.70	67.00	33.00	0.02	0.50	0.01
10500.0	34.00	2.72	7.09	4.68	73.90	11.60	62.40	86.90	13.10	0.01	0.50	0.00
10500.5	32.60	2.72	5.32	3.59	96.70	10.70	86.00	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 2. *Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10501.0	35.40	2.72	6.21	4.01	84.50	12.50	72.00	97.50	2.50	0.00	0.50	0.00
10501.5	33.70	2.72	7.77	5.15	61.40	11.40	50.00	74.40	25.60	0.01	0.50	0.01
10502.0	31.70	2.72	8.64	5.90	50.70	10.10	40.60	63.70	36.30	0.02	0.50	0.01
10502.5	28.00	2.72	7.79	5.61	51.70	7.80	43.80	64.70	35.30	0.02	0.50	0.01
10503.0	26.00	2.72	6.69	4.95	59.00	6.70	52.30	72.00	28.00	0.01	0.50	0.01
10503.5	30.90	2.72	6.62	4.58	70.10	9.60	60.60	83.10	16.90	0.01	0.50	0.00
10504.0	38.80	2.72	7.77	4.76	73.80	15.00	58.80	86.80	13.20	0.01	0.50	0.00
10504.5	46.40	2.73	8.67	4.64	77.70	21.60	56.10	90.70	9.30	0.00	0.50	0.00
10505.0	44.70	2.72	8.73	4.82	75.20	20.00	55.20	88.20	11.80	0.01	0.50	0.00
10505.5	43.60	2.72	8.78	4.95	74.10	19.00	55.10	87.10	12.90	0.01	0.50	0.00
10506.0	39.10	2.72	8.33	5.07	73.50	15.30	58.20	86.50	13.50	0.01	0.50	0.00
10506.5	43.20	2.72	8.64	4.90	77.40	18.70	58.70	90.40	9.60	0.01	0.50	0.00
10507.0	46.60	2.73	8.70	4.65	83.60	21.70	61.90	96.60	3.40	0.00	0.50	0.00
10507.5	49.40	2.73	10.36	5.24	72.70	24.40	48.30	85.70	14.30	0.01	0.50	0.00
10508.0	50.00	2.73	12.10	6.05	60.80	25.00	35.80	73.90	26.10	0.02	0.50	0.01
10508.5	46.10	2.73	13.69	7.38	49.80	21.20	28.50	62.80	37.20	0.03	0.50	0.01
10509.0	48.90	2.73	16.06	8.20	44.20	23.90	20.30	57.20	42.80	0.04	0.50	0.02
10509.5	48.40	2.73	18.23	9.40	37.50	23.40	14.00	50.50	49.50	0.05	0.50	0.02
10510.0	50.00	2.73	17.55	8.78	39.40	25.00	14.40	52.40	47.60	0.04	0.50	0.02
10510.5	45.70	2.72	14.78	8.03	40.90	20.80	20.10	53.90	46.10	0.04	0.50	0.02
10511.0	41.50	2.72	10.83	6.34	48.20	17.20	31.00	61.20	38.80	0.03	0.50	0.01
10511.5	35.90	2.72	8.62	5.52	54.50	12.90	41.60	67.50	32.50	0.02	0.50	0.01
10512.0	33.50	2.72	6.78	4.51	67.80	11.20	56.60	80.80	19.20	0.01	0.50	0.00
10512.5	25.70	2.72	5.44	4.05	73.60	6.60	67.00	86.60	13.40	0.01	0.50	0.00
10513.0	23.00	2.72	5.19	4.00	67.90	5.30	62.60	80.90	19.10	0.01	0.50	0.00
10513.5	13.90	2.71	4.75	4.09	64.10	1.90	62.20	77.10	22.90	0.01	0.50	0.01
10514.0	17.70	2.72	4.80	3.95	74.40	3.10	71.30	87.40	12.60	0.01	0.50	0.00
10514.5	23.00	2.72	5.04	3.88	87.60	5.30	82.30	100.00	0.00	0.00	0.00	0.00
10515.0	35.80	2.72	5.62	3.61	99.60	12.80	86.80	100.00	0.00	0.00	0.00	0.00
10515.5	40.10	2.72	5.29	3.17	100.00	16.10	83.90	100.00	0.00	0.00	0.00	0.00
10516.0	41.20	2.72	4.61	2.71	100.00	17.00	83.00	100.00	0.00	0.00	0.00	0.00
10516.5	42.50	2.72	4.80	2.76	100.00	18.10	81.90	100.00	0.00	0.00	0.00	0.00
10517.0	42.10	2.72	6.14	3.55	100.00	17.80	82.20	100.00	0.00	0.00	0.00	0.00
10517.5	42.60	2.72	7.45	4.28	92.50	18.20	74.30	100.00	0.00	0.00	0.00	0.00
10518.0	41.20	2.72	7.63	4.48	82.60	17.00	65.60	95.70	4.30	0.00	0.50	0.00
10518.5	35.10	2.72	6.91	4.49	75.50	12.30	63.20	88.50	11.50	0.01	0.50	0.00
10519.0	28.30	2.72	5.57	4.00	82.20	8.00	74.20	95.20	4.80	0.00	0.50	0.00
10519.5	22.80	2.72	4.74	3.66	91.90	5.20	86.70	100.00	0.00	0.00	0.00	0.00
10520.0	27.20	2.72	4.44	3.24	100.00	7.40	92.60	100.00	0.00	0.00	0.00	0.00
10520.5	26.70	2.72	4.57	3.35	100.00	7.10	92.90	100.00	0.00	0.00	0.00	0.00
10521.0	28.30	2.72	4.24	3.04	100.00	8.00	92.00	100.00	0.00	0.00	0.00	0.00
10521.5	24.70	2.72	3.80	2.86	100.00	6.10	93.90	100.00	0.00	0.00	0.00	0.00
10522.0	27.10	2.72	3.84	2.80	100.00	7.30	92.70	100.00	0.00	0.00	0.00	0.00
10522.5	27.50	2.72	4.28	3.10	100.00	7.60	92.40	100.00	0.00	0.00	0.00	0.00
10523.0	33.20	2.72	4.73	3.16	100.00	11.00	89.00	100.00	0.00	0.00	0.00	0.00
10523.5	30.60	2.72	4.99	3.46	100.00	9.40	90.60	100.00	0.00	0.00	0.00	0.00
10524.0	30.60	2.72	5.26	3.65	99.80	9.40	90.50	100.00	0.00	0.00	0.00	0.00
10524.5	29.80	2.72	5.94	4.17	86.30	8.90	77.50	99.40	0.60	0.00	0.50	0.00
10525.0	37.00	2.72	5.88	3.71	100.00	13.70	86.30	100.00	0.00	0.00	0.00	0.00
10525.5	41.10	2.72	5.94	3.50	100.00	16.90	83.10	100.00	0.00	0.00	0.00	0.00
10526.0	40.10	2.72	5.67	3.40	100.00	16.10	83.90	100.00	0.00	0.00	0.00	0.00

Appendix 2. *Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10526.5	41.40	2.72	5.78	3.39	100.00	17.10	82.90	100.00	0.00	0.00	0.00	0.00
10527.0	37.00	2.72	5.38	3.39	100.00	13.70	86.30	100.00	0.00	0.00	0.00	0.00
10527.5	36.20	2.72	4.79	3.05	100.00	13.10	86.90	100.00	0.00	0.00	0.00	0.00
10528.0	34.20	2.72	4.38	2.88	100.00	11.70	88.30	100.00	0.00	0.00	0.00	0.00
10528.5	38.70	2.72	4.06	2.49	100.00	14.90	85.10	100.00	0.00	0.00	0.00	0.00
10529.0	40.70	2.72	4.07	2.41	100.00	16.60	83.40	100.00	0.00	0.00	0.00	0.00
10529.5	45.30	2.72	4.18	2.29	100.00	20.50	79.50	100.00	0.00	0.00	0.00	0.00
10530.0	44.70	2.72	4.79	2.65	100.00	20.00	80.00	100.00	0.00	0.00	0.00	0.00
10530.5	50.20	2.73	4.72	2.35	100.00	25.20	74.80	100.00	0.00	0.00	0.00	0.00
10531.0	44.70	2.72	4.78	2.64	100.00	20.00	80.00	100.00	0.00	0.00	0.00	0.00
10531.5	47.20	2.73	4.95	2.62	100.00	22.30	77.70	100.00	0.00	0.00	0.00	0.00
10532.0	49.50	2.73	5.85	2.95	100.00	24.50	75.50	100.00	0.00	0.00	0.00	0.00
10532.5	49.70	2.73	6.46	3.25	100.00	24.70	75.30	100.00	0.00	0.00	0.00	0.00
10533.0	50.80	2.73	7.21	3.55	100.00	25.80	74.20	100.00	0.00	0.00	0.00	0.00
10533.5	49.70	2.73	7.37	3.71	100.00	24.70	75.30	100.00	0.00	0.00	0.00	0.00
10534.0	54.40	2.73	6.98	3.19	100.00	29.50	70.50	100.00	0.00	0.00	0.00	0.00
10534.5	52.40	2.73	5.97	2.84	100.00	27.40	72.60	100.00	0.00	0.00	0.00	0.00
10535.0	49.90	2.73	5.38	2.69	100.00	24.90	75.10	100.00	0.00	0.00	0.00	0.00
10535.5	46.80	2.73	5.21	2.77	100.00	21.90	78.10	100.00	0.00	0.00	0.00	0.00
10536.0	41.40	2.72	4.98	2.92	100.00	17.20	82.80	100.00	0.00	0.00	0.00	0.00
10536.5	37.20	2.72	4.91	3.08	100.00	13.90	86.10	100.00	0.00	0.00	0.00	0.00
10537.0	35.30	2.72	5.08	3.29	100.00	12.40	87.60	100.00	0.00	0.00	0.00	0.00
10537.5	34.90	2.72	4.79	3.11	100.00	12.20	87.80	100.00	0.00	0.00	0.00	0.00
10538.0	31.90	2.72	4.54	3.10	100.00	10.10	89.90	100.00	0.00	0.00	0.00	0.00
10538.5	30.70	2.72	4.68	3.24	100.00	9.40	90.60	100.00	0.00	0.00	0.00	0.00
10539.0	30.10	2.72	5.28	3.69	89.50	9.10	80.40	100.00	0.00	0.00	0.00	0.00
10539.5	31.10	2.72	5.42	3.73	89.10	9.70	79.50	100.00	0.00	0.00	0.00	0.00
10540.0	28.30	2.72	4.51	3.24	99.20	8.00	91.20	100.00	0.00	0.00	0.00	0.00
10540.5	25.30	2.72	3.41	2.55	100.00	6.40	93.60	100.00	0.00	0.00	0.00	0.00
10541.0	19.00	2.72	2.20	1.79	100.00	3.60	96.40	100.00	0.00	0.00	0.00	0.00
10541.5	14.30	2.71	1.24	1.06	100.00	2.00	98.00	100.00	0.00	0.00	0.00	0.00
10542.0	12.00	2.71	0.44	0.39	100.00	1.40	98.60	100.00	0.00	0.00	0.00	0.00
10542.5	15.80	2.72	0.48	0.40	100.00	2.50	97.50	100.00	0.00	0.00	0.00	0.00
10543.0	19.60	2.72	0.94	0.75	100.00	3.90	96.10	100.00	0.00	0.00	0.00	0.00
10543.5	24.00	2.72	1.47	1.12	100.00	5.80	94.20	100.00	0.00	0.00	0.00	0.00
10544.0	25.10	2.72	1.45	1.09	100.00	6.30	93.70	100.00	0.00	0.00	0.00	0.00
10544.5	23.80	2.72	1.45	1.11	100.00	5.70	94.30	100.00	0.00	0.00	0.00	0.00
10545.0	23.00	2.72	1.86	1.43	100.00	5.30	94.70	100.00	0.00	0.00	0.00	0.00
10545.5	21.20	2.72	2.50	1.97	100.00	4.50	95.50	100.00	0.00	0.00	0.00	0.00
10546.0	20.50	2.72	2.82	2.24	100.00	4.20	95.80	100.00	0.00	0.00	0.00	0.00
10546.5	18.30	2.72	2.87	2.34	100.00	3.30	96.70	100.00	0.00	0.00	0.00	0.00
10547.0	20.50	2.72	3.25	2.58	98.30	4.20	94.10	100.00	0.00	0.00	0.00	0.00
10547.5	26.30	2.72	3.57	2.63	96.80	6.90	89.80	100.00	0.00	0.00	0.00	0.00
10548.0	34.60	2.72	4.78	3.13	85.30	12.00	73.40	98.30	1.70	0.00	0.50	0.00
10548.5	39.80	2.72	5.39	3.25	86.10	15.80	70.30	99.20	0.80	0.00	0.50	0.00
10549.0	44.10	2.72	5.88	3.29	87.50	19.40	68.00	100.00	0.00	0.00	0.00	0.00
10549.5	46.40	2.73	5.88	3.15	98.30	21.60	76.70	100.00	0.00	0.00	0.00	0.00
10550.0	49.40	2.73	6.15	3.11	100.00	24.40	75.60	100.00	0.00	0.00	0.00	0.00
10550.5	48.90	2.73	6.38	3.26	98.50	23.90	74.50	100.00	0.00	0.00	0.00	0.00
10551.0	47.10	2.73	6.26	3.31	92.80	22.20	70.60	100.00	0.00	0.00	0.00	0.00
10551.5	45.90	2.73	6.40	3.46	87.00	21.10	65.90	100.00	0.00	0.00	0.50	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 2. *Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10552.0	46.20	2.73	7.24	3.90	79.60	21.30	58.30	92.60	7.40	0.00	0.50	0.00
10552.5	48.50	2.73	7.58	3.90	80.90	23.60	57.40	94.00	6.00	0.00	0.50	0.00
10553.0	46.10	2.73	7.60	4.10	77.30	21.20	56.10	90.30	9.70	0.00	0.50	0.00
10553.5	45.10	2.72	6.90	3.79	83.90	20.30	63.60	96.90	3.10	0.00	0.50	0.00
10554.0	42.20	2.72	6.99	4.04	78.60	17.80	60.80	91.60	8.40	0.00	0.50	0.00
10554.5	45.50	2.72	7.78	4.24	72.40	20.70	51.70	85.40	14.60	0.01	0.50	0.00
10555.0	45.40	2.72	8.95	4.89	59.40	20.60	38.90	72.50	27.50	0.01	0.50	0.01
10555.5	43.10	2.72	9.11	5.18	51.90	18.60	33.40	65.00	35.00	0.02	0.50	0.01
10556.0	38.80	2.72	7.98	4.88	53.60	15.00	38.60	66.60	33.40	0.02	0.50	0.01
10556.5	40.40	2.72	7.20	4.30	63.60	16.30	47.30	76.60	23.40	0.01	0.50	0.01
10557.0	44.50	2.72	7.76	4.31	66.60	19.80	46.80	79.60	20.40	0.01	0.50	0.00
10557.5	44.50	2.72	8.93	4.96	57.50	19.80	37.70	70.50	29.50	0.02	0.50	0.01
10558.0	43.40	2.72	9.67	5.47	51.80	18.80	33.00	64.80	35.20	0.02	0.50	0.01
10558.5	40.80	2.72	9.74	5.77	49.00	16.60	32.40	62.00	38.00	0.02	0.50	0.01
10559.0	39.90	2.72	9.95	5.98	47.90	15.90	32.00	60.90	39.10	0.02	0.50	0.01
10559.5	39.00	2.72	10.47	6.38	45.60	15.20	30.40	58.60	41.40	0.03	0.50	0.01
10560.0	44.70	2.72	10.54	5.83	51.00	20.00	31.00	64.00	36.00	0.02	0.50	0.01
10560.5	50.90	2.73	10.29	5.06	58.50	25.90	32.60	71.50	28.50	0.01	0.50	0.01
10561.0	56.70	2.73	10.19	4.42	67.60	32.10	35.50	80.60	19.40	0.01	0.50	0.00
10561.5	58.60	2.73	10.42	4.31	72.50	34.40	38.10	85.50	14.50	0.01	0.50	0.00
10562.0	54.70	2.73	10.62	4.81	65.10	29.90	35.10	78.10	21.90	0.01	0.50	0.01
10562.5	47.30	2.73	9.82	5.18	51.50	22.40	29.20	64.60	35.40	0.02	0.50	0.01
10563.0	38.20	2.72	8.62	5.33	39.60	14.60	25.00	52.60	47.40	0.03	0.50	0.01
10563.5	35.30	2.72	7.59	4.91	37.10	12.50	24.60	50.10	49.90	0.02	0.50	0.01
10564.0	36.10	2.72	7.69	4.92	40.70	13.00	27.70	53.70	46.30	0.02	0.50	0.01
10564.5	43.10	2.72	8.45	4.81	48.70	18.60	30.20	61.80	38.20	0.02	0.50	0.01
10565.0	48.00	2.73	9.26	4.81	51.00	23.10	27.90	64.00	36.00	0.02	0.50	0.01
10565.5	52.70	2.73	9.74	4.60	51.90	27.80	24.10	64.90	35.10	0.02	0.50	0.01
10566.0	49.70	2.73	10.45	5.26	43.40	24.70	18.80	56.40	43.60	0.02	0.50	0.01
10566.5	48.80	2.73	11.39	5.83	38.00	23.80	14.20	51.00	49.00	0.03	0.50	0.01
10567.0	47.60	2.73	12.32	6.46	33.60	22.60	11.00	46.60	53.40	0.04	0.50	0.02
10567.5	47.90	2.73	13.36	6.96	31.20	23.00	8.20	44.20	55.80	0.04	0.50	0.02
10568.0	52.10	2.73	12.72	6.09	35.50	27.20	8.30	48.50	51.50	0.03	0.50	0.02
10568.5	57.40	2.73	11.85	5.04	43.00	33.00	10.00	56.00	44.00	0.02	0.50	0.01
10569.0	53.70	2.73	10.64	4.92	48.40	28.90	19.50	61.40	38.60	0.02	0.50	0.01
10569.5	45.80	2.73	10.43	5.65	45.30	21.00	24.30	58.30	41.70	0.02	0.50	0.01
10570.0	38.50	2.72	10.24	6.30	42.00	14.80	27.20	55.00	45.00	0.03	0.50	0.01
10570.5	37.20	2.72	9.77	6.14	43.00	13.80	29.20	56.00	44.00	0.03	0.50	0.01
10571.0	30.90	2.72	8.73	6.04	43.30	9.50	33.80	56.40	43.60	0.03	0.50	0.01
10571.5	28.50	2.72	8.21	5.87	45.10	8.10	37.00	58.10	41.90	0.03	0.50	0.01
10572.0	34.90	2.72	7.85	5.11	52.10	12.20	39.90	65.10	34.90	0.02	0.50	0.01
10572.5	43.90	2.72	8.05	4.51	59.10	19.30	39.90	72.20	27.80	0.01	0.50	0.01
10573.0	44.00	2.72	7.13	3.99	67.40	19.30	48.10	80.40	19.60	0.01	0.50	0.00
10573.5	44.70	2.72	6.05	3.35	81.80	20.00	61.80	94.80	5.20	0.00	0.50	0.00
10574.0	46.70	2.73	5.82	3.11	88.60	21.80	66.80	100.00	0.00	0.00	0.00	0.00
10574.5	55.10	2.73	6.72	3.02	89.90	30.30	59.60	100.00	0.00	0.00	0.00	0.00
10575.0	53.60	2.73	7.08	3.29	80.40	28.70	51.70	93.40	6.60	0.00	0.50	0.00
10575.5	58.80	2.73	6.92	2.85	90.80	34.60	56.30	100.00	0.00	0.00	0.00	0.00
10576.0	56.10	2.73	6.42	2.82	91.60	31.50	60.10	100.00	0.00	0.00	0.00	0.00
10576.5	54.60	2.73	6.89	3.13	82.20	29.80	52.40	95.20	4.80	0.00	0.50	0.00
10577.0	51.40	2.73	6.92	3.37	74.90	26.40	48.50	88.00	12.00	0.00	0.50	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 2. *Log Analysis of the Bruin 1 Sylvia Young Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
10577.5	46.90	2.73	6.29	3.34	78.00	22.00	56.00	91.00	9.00	0.00	0.50	0.00
10578.0	48.20	2.73	5.03	2.61	98.40	23.20	75.20	100.00	0.00	0.00	0.00	0.00
10578.5	46.30	2.73	4.08	2.19	100.00	21.40	78.60	100.00	0.00	0.00	0.00	0.00
10579.0	49.10	2.73	3.79	1.93	100.00	24.20	75.80	100.00	0.00	0.00	0.00	0.00
10579.5	49.90	2.73	3.39	1.70	100.00	24.90	75.10	100.00	0.00	0.00	0.00	0.00
10580.0	49.30	2.73	3.02	1.53	100.00	24.30	75.70	100.00	0.00	0.00	0.00	0.00
10580.5	47.10	2.73	2.67	1.41	100.00	22.10	77.90	100.00	0.00	0.00	0.00	0.00
10581.0	48.80	2.73	3.00	1.54	100.00	23.80	76.20	100.00	0.00	0.00	0.00	0.00
10581.5	49.90	2.73	3.34	1.67	100.00	24.90	75.10	100.00	0.00	0.00	0.00	0.00
10582.0	55.70	2.73	3.99	1.77	100.00	31.10	68.90	100.00	0.00	0.00	0.00	0.00
10582.5	57.40	2.73	4.48	1.91	100.00	33.00	67.00	100.00	0.00	0.00	0.00	0.00
10583.0	56.10	2.73	4.82	2.12	100.00	31.50	68.50	100.00	0.00	0.00	0.00	0.00
10583.5	55.10	2.73	4.82	2.16	100.00	30.40	69.60	100.00	0.00	0.00	0.00	0.00
10584.0	54.80	2.73	4.79	2.16	100.00	30.10	69.90	100.00	0.00	0.00	0.00	0.00
10584.5	60.00	2.73	5.02	2.01	100.00	36.00	64.00	100.00	0.00	0.00	0.00	0.00
10585.0	57.30	2.73	5.22	2.23	100.00	32.90	67.10	100.00	0.00	0.00	0.00	0.00
10585.5	55.40	2.73	5.60	2.49	100.00	30.70	69.30	100.00	0.00	0.00	0.00	0.00
10586.0	50.80	2.73	5.58	2.75	100.00	25.80	74.20	100.00	0.00	0.00	0.00	0.00
10586.5	52.10	2.73	5.58	2.67	100.00	27.20	72.80	100.00	0.00	0.00	0.00	0.00
10587.0	51.30	2.73	5.52	2.69	100.00	26.30	73.70	100.00	0.00	0.00	0.00	0.00
10587.5	51.10	2.73	6.03	2.95	100.00	26.20	73.80	100.00	0.00	0.00	0.00	0.00
10588.0	48.80	2.73	6.83	3.50	90.90	23.80	67.00	100.00	0.00	0.00	0.00	0.00
10588.5	48.10	2.73	7.50	3.89	78.40	23.10	55.30	91.40	8.60	0.00	0.50	0.00
10589.0	46.40	2.73	7.51	4.03	73.80	21.50	52.30	86.80	13.20	0.01	0.50	0.00
10589.5	47.40	2.73	7.06	3.71	77.60	22.50	55.10	90.60	9.40	0.00	0.50	0.00
10590.0	44.80	2.72	6.57	3.63	80.10	20.10	60.00	93.10	6.90	0.00	0.50	0.00
10590.5	46.30	2.73	6.60	3.54	84.20	21.50	62.70	97.20	2.80	0.00	0.50	0.00
10591.0	42.40	2.72	6.34	3.65	82.70	17.90	64.80	95.70	4.30	0.00	0.50	0.00
10591.5	45.00	2.72	6.58	3.62	83.60	20.20	63.40	96.60	3.40	0.00	0.50	0.00
10592.0	46.70	2.73	6.84	3.65	84.70	21.80	62.90	97.70	2.30	0.00	0.50	0.00
10592.5	51.30	2.73	6.94	3.38	94.50	26.30	68.20	100.00	0.00	0.00	0.00	0.00
10593.0	50.10	2.73	6.46	3.23	100.00	25.10	74.90	100.00	0.00	0.00	0.00	0.00
10593.5	47.20	2.73	5.19	2.74	100.00	22.30	77.70	100.00	0.00	0.00	0.00	0.00
10594.0	48.00	2.73	5.26	2.73	100.00	23.10	76.90	100.00	0.00	0.00	0.00	0.00
10594.5	45.80	2.73	5.00	2.71	100.00	21.00	79.00	100.00	0.00	0.00	0.00	0.00
10595.0	45.00	2.72	5.41	2.97	100.00	20.30	79.70	100.00	0.00	0.00	0.00	0.00
10595.5	40.90	2.72	5.44	3.22	100.00	16.80	83.20	100.00	0.00	0.00	0.00	0.00
10596.0	41.50	2.72	5.55	3.24	100.00	17.30	82.70	100.00	0.00	0.00	0.00	0.00
10596.5	43.20	2.72	5.73	3.25	100.00	18.70	81.30	100.00	0.00	0.00	0.00	0.00
10597.0	46.70	2.73	5.40	2.88	100.00	21.80	78.20	100.00	0.00	0.00	0.00	0.00
10597.5	51.10	2.73	4.62	2.26	100.00	26.20	73.80	100.00	0.00	0.00	0.00	0.00
10598.0	51.90	2.73	3.71	1.79	100.00	26.90	73.10	100.00	0.00	0.00	0.00	0.00
10598.5	50.30	2.73	2.47	1.23	100.00	25.30	74.70	100.00	0.00	0.00	0.00	0.00
10599.0	39.60	2.72	1.82	1.10	100.00	15.70	84.30	100.00	0.00	0.00	0.00	0.00
10599.5	34.20	2.72	1.41	0.93	100.00	11.70	88.30	100.00	0.00	0.00	0.00	0.00
10600.0	33.90	2.72	1.83	1.21	100.00	11.50	88.50	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_e h$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11850.0	81.80	2.73	6.84	1.24	100.00	67.00	33.00	100.00	0.00	0.00	0.00	0.00
11850.5	72.90	2.73	5.96	1.61	100.00	53.20	46.80	100.00	0.00	0.00	0.00	0.00
11851.0	67.20	2.73	5.39	1.77	100.00	45.10	54.90	100.00	0.00	0.00	0.00	0.00
11851.5	66.90	2.73	5.44	1.80	100.00	44.80	55.20	100.00	0.00	0.00	0.00	0.00
11852.0	70.40	2.73	5.52	1.63	100.00	49.60	50.40	100.00	0.00	0.00	0.00	0.00
11852.5	76.70	2.73	5.26	1.23	100.00	58.80	41.20	100.00	0.00	0.00	0.00	0.00
11853.0	79.00	2.73	5.28	1.11	100.00	62.40	37.60	100.00	0.00	0.00	0.00	0.00
11853.5	76.40	2.73	5.72	1.35	100.00	58.30	41.70	100.00	0.00	0.00	0.00	0.00
11854.0	76.10	2.73	6.22	1.49	100.00	58.00	42.00	100.00	0.00	0.00	0.00	0.00
11854.5	74.60	2.73	6.65	1.69	100.00	55.70	44.30	100.00	0.00	0.00	0.00	0.00
11855.0	74.30	2.73	7.20	1.85	100.00	55.30	44.70	100.00	0.00	0.00	0.00	0.00
11855.5	77.20	2.73	7.66	1.75	100.00	59.60	40.40	100.00	0.00	0.00	0.00	0.00
11856.0	78.20	2.73	7.30	1.59	100.00	61.10	38.90	100.00	0.00	0.00	0.00	0.00
11856.5	79.80	2.73	6.48	1.31	100.00	63.70	36.30	100.00	0.00	0.00	0.00	0.00
11857.0	80.00	2.73	6.26	1.25	100.00	64.00	36.00	100.00	0.00	0.00	0.00	0.00
11857.5	76.10	2.73	6.38	1.52	100.00	58.00	42.00	100.00	0.00	0.00	0.00	0.00
11858.0	75.80	2.73	6.47	1.57	100.00	57.40	42.60	100.00	0.00	0.00	0.00	0.00
11858.5	78.90	2.73	6.60	1.39	100.00	62.30	37.70	100.00	0.00	0.00	0.00	0.00
11859.0	81.80	2.73	6.92	1.26	100.00	66.80	33.20	100.00	0.00	0.00	0.00	0.00
11859.5	86.80	2.74	7.74	1.02	100.00	75.40	24.60	100.00	0.00	0.00	0.00	0.00
11860.0	87.80	2.74	8.24	1.00	100.00	77.10	22.90	100.00	0.00	0.00	0.00	0.00
11860.5	80.50	2.73	7.79	1.52	100.00	64.80	35.20	100.00	0.00	0.00	0.00	0.00
11861.0	73.10	2.73	6.92	1.86	100.00	53.50	46.50	100.00	0.00	0.00	0.00	0.00
11861.5	74.20	2.73	6.23	1.61	100.00	55.10	44.90	100.00	0.00	0.00	0.00	0.00
11862.0	78.30	2.73	6.02	1.31	100.00	61.40	38.60	100.00	0.00	0.00	0.00	0.00
11862.5	82.60	2.73	6.12	1.06	100.00	68.30	31.70	100.00	0.00	0.00	0.00	0.00
11863.0	87.20	2.74	6.40	0.82	100.00	76.00	24.00	100.00	0.00	0.00	0.00	0.00
11863.5	89.90	2.74	7.02	0.71	100.00	80.90	19.10	100.00	0.00	0.00	0.00	0.00
11864.0	91.80	2.74	7.47	0.61	100.00	84.30	15.70	100.00	0.00	0.00	0.00	0.00
11864.5	92.00	2.74	7.41	0.59	100.00	84.60	15.40	100.00	0.00	0.00	0.00	0.00
11865.0	88.90	2.74	7.32	0.81	100.00	79.00	21.00	100.00	0.00	0.00	0.00	0.00
11865.5	86.30	2.74	7.54	1.03	100.00	74.60	25.40	100.00	0.00	0.00	0.00	0.00
11866.0	88.20	2.74	7.70	0.91	100.00	77.70	22.30	100.00	0.00	0.00	0.00	0.00
11866.5	86.80	2.74	7.42	0.98	100.00	75.30	24.70	100.00	0.00	0.00	0.00	0.00
11867.0	80.60	2.73	6.99	1.36	100.00	65.00	35.00	100.00	0.00	0.00	0.00	0.00
11867.5	77.00	2.73	6.34	1.46	100.00	59.20	40.80	100.00	0.00	0.00	0.00	0.00
11868.0	81.30	2.73	6.05	1.13	100.00	66.10	33.90	100.00	0.00	0.00	0.00	0.00
11868.5	85.30	2.74	6.29	0.93	100.00	72.70	27.30	100.00	0.00	0.00	0.00	0.00
11869.0	82.60	2.73	6.31	1.10	100.00	68.30	31.70	100.00	0.00	0.00	0.00	0.00
11869.5	80.60	2.73	6.33	1.23	100.00	65.00	35.00	100.00	0.00	0.00	0.00	0.00
11870.0	82.80	2.73	6.47	1.11	100.00	68.60	31.40	100.00	0.00	0.00	0.00	0.00
11870.5	85.70	2.74	6.51	0.93	100.00	73.40	26.60	100.00	0.00	0.00	0.00	0.00
11871.0	85.50	2.74	6.79	0.98	100.00	73.20	26.80	100.00	0.00	0.00	0.00	0.00
11871.5	86.30	2.74	7.29	1.00	100.00	74.60	25.40	100.00	0.00	0.00	0.00	0.00
11872.0	89.70	2.74	7.39	0.76	100.00	80.50	19.50	100.00	0.00	0.00	0.00	0.00
11872.5	90.30	2.74	7.48	0.73	100.00	81.50	18.50	100.00	0.00	0.00	0.00	0.00
11873.0	84.50	2.74	8.18	1.27	100.00	71.40	28.60	100.00	0.00	0.00	0.00	0.00
11873.5	75.30	2.73	8.84	2.18	100.00	56.70	43.30	100.00	0.00	0.00	0.00	0.00
11874.0	65.80	2.73	8.75	3.00	100.00	43.20	56.80	100.00	0.00	0.00	0.00	0.00
11874.5	63.80	2.73	8.62	3.12	100.00	40.80	59.20	100.00	0.00	0.00	0.00	0.00
11875.0	65.30	2.73	8.94	3.10	100.00	42.70	57.30	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11875.5	61.50	2.73	9.24	3.56	87.20	37.80	49.40	100.00	0.00	0.00	0.00	0.00
11876.0	60.60	2.73	9.60	3.79	64.40	36.70	27.70	77.40	22.60	0.01	0.50	33.23
11876.5	65.20	2.73	10.00	3.48	72.40	42.50	29.90	85.40	14.60	0.01	0.50	19.70
11877.0	70.20	2.73	10.17	3.03	88.00	49.30	38.70	100.00	0.00	0.00	0.00	0.00
11877.5	70.20	2.73	10.01	2.98	91.40	49.30	42.10	100.00	0.00	0.00	0.00	0.00
11878.0	62.50	2.73	9.44	3.54	78.40	39.00	39.40	91.50	8.50	0.00	0.50	11.74
11878.5	56.20	2.73	9.34	4.09	68.50	31.60	36.90	81.50	18.50	0.01	0.50	29.27
11879.0	53.70	2.72	10.08	4.67	61.70	28.80	32.80	74.70	25.30	0.01	0.50	45.84
11879.5	54.70	2.72	10.64	4.82	56.20	29.90	26.20	69.20	30.80	0.02	0.50	57.51
11880.0	60.70	2.73	10.85	4.27	57.60	36.80	20.80	70.60	29.40	0.01	0.50	48.63
11880.5	70.30	2.73	11.19	3.33	69.80	49.40	20.40	82.80	17.20	0.01	0.50	22.12
11881.0	78.60	2.73	11.76	2.52	100.00	61.70	38.30	100.00	0.00	0.00	0.00	0.00
11881.5	76.50	2.73	11.75	2.76	100.00	58.50	41.50	100.00	0.00	0.00	0.00	0.00
11882.0	69.80	2.73	10.97	3.31	98.20	48.80	49.40	100.00	0.00	0.00	0.00	0.00
11882.5	64.90	2.73	10.35	3.63	94.30	42.10	52.20	100.00	0.00	0.00	0.00	0.00
11883.0	64.50	2.73	10.10	3.59	94.90	41.60	53.30	100.00	0.00	0.00	0.00	0.00
11883.5	64.70	2.73	9.72	3.43	95.60	41.80	53.80	100.00	0.00	0.00	0.00	0.00
11884.0	62.20	2.73	9.59	3.63	86.60	38.70	48.00	99.70	0.30	0.00	0.50	0.49
11884.5	56.70	2.73	9.58	4.15	76.80	32.10	44.70	89.80	10.20	0.00	0.50	16.38
11885.0	46.80	2.72	8.83	4.70	68.40	21.90	46.50	81.40	18.60	0.01	0.50	33.83
11885.5	42.90	2.72	8.13	4.65	68.10	18.40	49.80	81.10	18.90	0.01	0.50	34.00
11886.0	45.90	2.72	8.01	4.33	73.30	21.00	52.30	86.30	13.70	0.01	0.50	22.99
11886.5	45.40	2.72	7.87	4.29	73.90	20.60	53.30	87.00	13.00	0.01	0.50	21.71
11887.0	45.50	2.72	7.86	4.29	72.50	20.70	51.80	85.50	14.50	0.01	0.50	24.14
11887.5	48.60	2.72	8.61	4.43	68.90	23.60	45.30	81.90	18.10	0.01	0.50	31.05
11888.0	48.80	2.72	9.61	4.92	63.30	23.80	39.50	76.30	23.70	0.01	0.50	45.15
11888.5	48.30	2.72	10.08	5.21	61.80	23.30	38.50	74.80	25.20	0.01	0.50	50.92
11889.0	49.50	2.72	10.18	5.14	60.80	24.50	36.30	73.90	26.10	0.01	0.50	52.13
11889.5	46.00	2.72	10.07	5.44	54.80	21.10	33.70	67.80	32.20	0.02	0.50	67.90
11890.0	40.00	2.72	9.64	5.78	50.30	16.00	34.30	63.30	36.70	0.02	0.50	82.27
11890.5	36.40	2.72	9.10	5.79	49.00	13.20	35.70	62.00	38.00	0.02	0.50	85.34
11891.0	35.70	2.72	9.20	5.92	45.50	12.70	32.80	58.50	41.50	0.03	0.50	95.15
11891.5	37.90	2.72	9.84	6.11	41.00	14.40	26.60	54.00	46.00	0.03	0.50	108.84
11892.0	40.10	2.72	10.66	6.39	38.90	16.10	22.80	51.90	48.10	0.03	0.50	119.14
11892.5	39.50	2.72	11.05	6.68	35.40	15.60	19.80	48.40	51.60	0.03	0.50	133.63
11893.0	39.90	2.72	11.01	6.61	35.50	15.90	19.60	48.50	51.50	0.03	0.50	132.04
11893.5	44.20	2.72	11.08	6.18	34.90	19.60	15.30	47.90	52.10	0.03	0.50	124.84
11894.0	45.50	2.72	11.01	6.01	32.70	20.70	12.00	45.70	54.30	0.03	0.50	126.57
11894.5	43.10	2.72	10.71	6.10	28.70	18.50	10.10	41.70	58.30	0.04	0.50	137.89
11895.0	42.90	2.72	10.15	5.79	27.60	18.40	9.20	40.60	59.40	0.03	0.50	133.50
11895.5	43.30	2.72	9.62	5.45	28.40	18.80	9.60	41.40	58.60	0.03	0.50	123.93
11896.0	40.90	2.72	9.25	5.47	24.30	16.70	7.60	37.30	62.70	0.03	0.50	132.88
11896.5	39.20	2.72	9.03	5.49	24.50	15.40	9.20	37.60	62.40	0.03	0.50	132.91
11897.0	41.10	2.72	9.31	5.48	29.70	16.90	12.80	42.70	57.30	0.03	0.50	121.78
11897.5	44.40	2.72	9.82	5.46	30.70	19.70	11.00	43.70	56.30	0.03	0.50	119.10
11898.0	48.00	2.72	9.80	5.09	34.40	23.00	11.40	47.50	52.50	0.03	0.50	103.80
11898.5	48.00	2.72	8.81	4.58	39.60	23.00	16.60	52.70	47.30	0.02	0.50	84.09
11899.0	43.10	2.72	7.90	4.49	41.20	18.60	22.60	54.20	45.80	0.02	0.50	79.68
11899.5	39.00	2.72	7.62	4.65	44.70	15.20	29.50	57.70	42.30	0.02	0.50	76.22
11900.0	38.50	2.72	7.61	4.68	46.00	14.80	31.20	59.00	41.00	0.02	0.50	74.40
11900.5	43.50	2.72	8.18	4.62	59.00	18.90	40.00	72.00	28.00	0.01	0.50	50.22

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11901.0	53.70	2.72	8.67	4.02	58.60	28.80	29.80	71.60	28.40	0.01	0.50	44.19
11901.5	61.50	2.73	8.85	3.40	58.20	37.90	20.30	71.20	28.80	0.01	0.50	38.01
11902.0	63.20	2.73	9.15	3.37	47.70	39.90	7.80	60.80	39.20	0.01	0.50	51.27
11902.5	58.30	2.73	9.21	3.85	54.60	33.90	20.70	67.70	32.30	0.01	0.50	48.24
11903.0	55.50	2.72	9.13	4.07	61.90	30.80	31.10	74.90	25.10	0.01	0.50	39.52
11903.5	60.20	2.73	8.92	3.55	84.20	36.20	48.00	97.20	2.80	0.00	0.50	3.85
11904.0	66.40	2.73	8.85	2.97	100.00	44.10	55.90	100.00	0.00	0.00	0.00	0.00
11904.5	70.50	2.73	9.31	2.74	100.00	49.70	50.30	100.00	0.00	0.00	0.00	0.00
11905.0	72.20	2.73	9.83	2.73	100.00	52.20	47.80	100.00	0.00	0.00	0.00	0.00
11905.5	74.10	2.73	9.79	2.53	100.00	55.00	45.00	100.00	0.00	0.00	0.00	0.00
11906.0	72.10	2.73	9.05	2.52	100.00	52.00	48.00	100.00	0.00	0.00	0.00	0.00
11906.5	64.90	2.73	8.33	2.92	100.00	42.10	57.90	100.00	0.00	0.00	0.00	0.00
11907.0	53.60	2.72	7.82	3.63	97.90	28.70	69.10	100.00	0.00	0.00	0.00	0.00
11907.5	40.00	2.72	7.37	4.42	75.90	16.00	59.90	89.00	11.00	0.01	0.50	18.93
11908.0	34.30	2.72	7.51	4.94	59.10	11.70	47.40	72.10	27.90	0.01	0.50	53.38
11908.5	36.60	2.72	7.88	4.99	50.00	13.40	36.60	63.00	37.00	0.02	0.50	71.63
11909.0	37.40	2.72	7.51	4.71	49.00	14.00	35.00	62.00	38.00	0.02	0.50	69.32
11909.5	35.30	2.72	6.68	4.32	55.50	12.40	43.00	68.50	31.50	0.01	0.50	52.85
11910.0	35.10	2.72	6.33	4.11	60.80	12.30	48.50	73.80	26.20	0.01	0.50	41.84
11910.5	35.20	2.72	6.04	3.91	60.60	12.40	48.20	73.60	26.40	0.01	0.50	40.01
11911.0	36.00	2.72	5.50	3.52	62.70	13.00	49.80	75.80	24.20	0.01	0.50	33.09
11911.5	38.90	2.72	5.60	3.43	69.70	15.10	54.60	82.70	17.30	0.01	0.50	22.97
11912.0	41.60	2.72	5.89	3.44	72.40	17.30	55.10	85.40	14.60	0.01	0.50	19.44
11912.5	38.90	2.72	5.74	3.51	73.40	15.10	58.30	86.40	13.60	0.01	0.50	18.47
11913.0	32.70	2.72	5.42	3.65	76.40	10.70	65.80	89.50	10.50	0.00	0.50	14.94
11913.5	29.20	2.72	5.31	3.76	81.80	8.50	73.30	94.80	5.20	0.00	0.50	7.54
11914.0	28.70	2.72	5.36	3.82	90.30	8.20	82.10	100.00	0.00	0.00	0.00	0.00
11914.5	31.00	2.72	5.72	3.95	92.20	9.60	82.60	100.00	0.00	0.00	0.00	0.00
11915.0	32.90	2.72	6.39	4.29	82.40	10.80	71.60	95.40	4.60	0.00	0.50	7.62
11915.5	34.80	2.72	6.72	4.38	77.20	12.10	65.10	90.20	9.80	0.00	0.50	16.63
11916.0	37.70	2.72	6.85	4.27	76.70	14.20	62.50	89.70	10.30	0.00	0.50	16.99
11916.5	35.60	2.72	6.84	4.41	75.00	12.70	62.30	88.00	12.00	0.01	0.50	20.51
11917.0	32.00	2.72	6.71	4.57	72.50	10.20	62.30	85.50	14.50	0.01	0.50	25.69
11917.5	32.10	2.72	6.62	4.49	72.20	10.30	61.90	85.20	14.80	0.01	0.50	25.74
11918.0	33.70	2.72	6.43	4.27	74.90	11.30	63.50	87.90	12.10	0.01	0.50	20.06
11918.5	35.90	2.72	6.24	4.00	80.50	12.90	67.60	93.50	6.50	0.00	0.50	10.02
11919.0	37.20	2.72	6.13	3.85	81.60	13.80	67.70	94.60	5.40	0.00	0.50	8.07
11919.5	35.60	2.72	6.00	3.86	79.50	12.70	66.80	92.50	7.50	0.00	0.50	11.20
11920.0	34.20	2.72	6.09	4.01	78.40	11.70	66.70	91.40	8.60	0.00	0.50	13.30
11920.5	33.10	2.72	6.53	4.37	72.20	11.00	61.30	85.20	14.80	0.01	0.50	25.00
11921.0	36.00	2.72	6.52	4.18	75.00	13.00	62.00	88.00	12.00	0.01	0.50	19.44
11921.5	41.50	2.72	6.44	3.76	80.50	17.30	63.30	93.60	6.40	0.00	0.50	9.39
11922.0	44.60	2.72	6.77	3.75	76.20	19.90	56.30	89.20	10.80	0.00	0.50	15.71
11922.5	47.00	2.72	6.98	3.70	78.10	22.10	56.10	91.20	8.80	0.00	0.50	12.70
11923.0	50.30	2.72	7.34	3.65	87.90	25.30	62.60	100.00	0.00	0.00	0.00	0.00
11923.5	53.20	2.72	7.86	3.68	94.90	28.30	66.60	100.00	0.00	0.00	0.00	0.00
11924.0	54.20	2.72	7.76	3.55	100.00	29.40	70.60	100.00	0.00	0.00	0.00	0.00
11924.5	52.00	2.72	7.03	3.37	100.00	27.10	72.90	100.00	0.00	0.00	0.00	0.00
11925.0	45.20	2.72	5.88	3.22	100.00	20.40	79.60	100.00	0.00	0.00	0.00	0.00
11925.5	35.30	2.72	4.46	2.88	100.00	12.40	87.60	100.00	0.00	0.00	0.00	0.00
11926.0	24.50	2.71	3.69	2.78	100.00	6.00	94.00	100.00	0.00	0.00	0.00	0.00

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11926.5	20.50	2.71	3.18	2.52	100.00	4.20	95.80	100.00	0.00	0.00	0.00	0.00
11927.0	25.60	2.71	2.98	2.22	100.00	6.60	93.40	100.00	0.00	0.00	0.00	0.00
11927.5	29.90	2.72	3.91	2.74	100.00	8.90	91.10	100.00	0.00	0.00	0.00	0.00
11928.0	33.90	2.72	5.16	3.41	100.00	11.50	88.50	100.00	0.00	0.00	0.00	0.00
11928.5	43.00	2.72	5.77	3.29	100.00	18.50	81.50	100.00	0.00	0.00	0.00	0.00
11929.0	51.20	2.72	5.91	2.88	100.00	26.20	73.80	100.00	0.00	0.00	0.00	0.00
11929.5	51.50	2.72	6.18	3.00	100.00	26.50	73.50	100.00	0.00	0.00	0.00	0.00
11930.0	46.50	2.72	6.54	3.50	100.00	21.60	78.40	100.00	0.00	0.00	0.00	0.00
11930.5	44.90	2.72	6.85	3.78	97.50	20.10	77.30	100.00	0.00	0.00	0.00	0.00
11931.0	48.50	2.72	7.33	3.78	93.70	23.50	70.20	100.00	0.00	0.00	0.00	0.00
11931.5	50.00	2.72	7.67	3.84	94.50	25.00	69.50	100.00	0.00	0.00	0.00	0.00
11932.0	52.90	2.72	7.62	3.59	99.20	27.90	71.30	100.00	0.00	0.00	0.00	0.00
11932.5	53.70	2.72	7.60	3.52	88.40	28.80	59.60	100.00	0.00	0.00	0.00	0.00
11933.0	48.60	2.72	7.40	3.80	64.20	23.60	40.60	77.20	22.80	0.01	0.50	33.63
11933.5	43.20	2.72	6.46	3.67	59.30	18.60	40.60	72.30	27.70	0.01	0.50	39.44
11934.0	39.30	2.72	5.54	3.36	64.30	15.40	48.90	77.40	22.60	0.01	0.50	29.53
11934.5	37.10	2.72	5.65	3.56	67.30	13.80	53.50	80.30	19.70	0.01	0.50	27.18
11935.0	35.10	2.72	6.17	4.01	64.10	12.30	51.80	77.10	22.90	0.01	0.50	35.62
11935.5	33.70	2.72	6.05	4.01	58.90	11.30	47.60	72.00	28.00	0.01	0.50	43.65
11936.0	28.40	2.72	5.32	3.81	64.10	8.00	56.10	77.10	22.90	0.01	0.50	33.80
11936.5	18.90	2.71	4.37	3.54	66.60	3.60	63.10	79.60	20.40	0.01	0.50	27.96
11937.0	16.10	2.71	3.93	3.30	76.30	2.60	73.70	89.30	10.70	0.00	0.50	13.71
11937.5	18.80	2.71	4.19	3.40	79.00	3.50	75.50	92.00	8.00	0.00	0.50	10.55
11938.0	18.20	2.71	4.00	3.27	88.50	3.30	85.20	100.00	0.00	0.00	0.00	0.00
11938.5	16.40	2.71	3.18	2.66	100.00	2.70	97.30	100.00	0.00	0.00	0.00	0.00
11939.0	15.30	2.71	2.43	2.06	100.00	2.30	97.70	100.00	0.00	0.00	0.00	0.00
11939.5	14.80	2.71	2.15	1.84	100.00	2.20	97.80	100.00	0.00	0.00	0.00	0.00
11940.0	17.50	2.71	2.33	1.92	100.00	3.10	96.90	100.00	0.00	0.00	0.00	0.00
11940.5	22.90	2.71	2.93	2.26	100.00	5.20	94.80	100.00	0.00	0.00	0.00	0.00
11941.0	32.50	2.72	4.36	2.94	100.00	10.60	89.40	100.00	0.00	0.00	0.00	0.00
11941.5	41.50	2.72	5.55	3.25	100.00	17.20	82.80	100.00	0.00	0.00	0.00	0.00
11942.0	39.80	2.72	5.39	3.25	100.00	15.80	84.20	100.00	0.00	0.00	0.00	0.00
11942.5	36.50	2.72	4.90	3.11	100.00	13.30	86.70	100.00	0.00	0.00	0.00	0.00
11943.0	36.30	2.72	4.68	2.98	100.00	13.20	86.80	100.00	0.00	0.00	0.00	0.00
11943.5	40.70	2.72	4.56	2.71	100.00	16.50	83.50	100.00	0.00	0.00	0.00	0.00
11944.0	44.80	2.72	4.41	2.43	100.00	20.10	79.90	100.00	0.00	0.00	0.00	0.00
11944.5	42.70	2.72	3.97	2.28	100.00	18.20	81.80	100.00	0.00	0.00	0.00	0.00
11945.0	42.40	2.72	3.90	2.24	100.00	18.00	82.00	100.00	0.00	0.00	0.00	0.00
11945.5	42.40	2.72	4.21	2.43	100.00	17.90	82.10	100.00	0.00	0.00	0.00	0.00
11946.0	40.70	2.72	4.11	2.44	100.00	16.60	83.40	100.00	0.00	0.00	0.00	0.00
11946.5	38.60	2.72	4.01	2.46	100.00	14.90	85.10	100.00	0.00	0.00	0.00	0.00
11947.0	38.70	2.72	4.32	2.65	100.00	15.00	85.00	100.00	0.00	0.00	0.00	0.00
11947.5	39.40	2.72	4.34	2.63	100.00	15.50	84.50	100.00	0.00	0.00	0.00	0.00
11948.0	38.30	2.72	3.77	2.33	100.00	14.60	85.40	100.00	0.00	0.00	0.00	0.00
11948.5	37.00	2.72	3.09	1.95	100.00	13.70	86.30	100.00	0.00	0.00	0.00	0.00
11949.0	34.40	2.72	3.03	1.99	100.00	11.80	88.20	100.00	0.00	0.00	0.00	0.00
11949.5	36.40	2.72	4.12	2.62	100.00	13.30	86.70	100.00	0.00	0.00	0.00	0.00
11950.0	46.50	2.72	5.47	2.93	100.00	21.60	78.40	100.00	0.00	0.00	0.00	0.00
11950.5	57.10	2.73	6.19	2.66	100.00	32.60	67.40	100.00	0.00	0.00	0.00	0.00
11951.0	61.00	2.73	6.89	2.69	100.00	37.20	62.80	100.00	0.00	0.00	0.00	0.00
11951.5	58.90	2.73	7.31	3.01	100.00	34.70	65.30	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth	V_{clay}	Rho_{ma}	Phi_t	Phi_e	Sw_{Archie}	Sw_b	Sw_f	Sw_t	S_{hc} (So+Sg)	$SoPhi_e$	h	$SoPhi_eh$
(ft KB)	(%)	(gm/cc)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(interval)	(ft)	
11952.0	54.10	2.72	6.94	3.18	100.00	29.30	70.70	100.00	0.00	0.00	0.00	0.00
11952.5	49.90	2.72	6.52	3.27	100.00	24.90	75.10	100.00	0.00	0.00	0.00	0.00
11953.0	47.50	2.72	6.14	3.22	100.00	22.60	77.40	100.00	0.00	0.00	0.00	0.00
11953.5	51.80	2.72	6.07	2.93	100.00	26.80	73.20	100.00	0.00	0.00	0.00	0.00
11954.0	57.20	2.73	6.52	2.79	100.00	32.70	67.30	100.00	0.00	0.00	0.00	0.00
11954.5	55.20	2.72	6.48	2.90	100.00	30.50	69.50	100.00	0.00	0.00	0.00	0.00
11955.0	49.60	2.72	5.77	2.90	100.00	24.60	75.40	100.00	0.00	0.00	0.00	0.00
11955.5	47.70	2.72	5.27	2.76	100.00	22.70	77.30	100.00	0.00	0.00	0.00	0.00
11956.0	48.40	2.72	5.38	2.78	100.00	23.40	76.60	100.00	0.00	0.00	0.00	0.00
11956.5	50.40	2.72	5.89	2.92	100.00	25.40	74.60	100.00	0.00	0.00	0.00	0.00
11957.0	53.20	2.72	6.80	3.18	100.00	28.30	71.70	100.00	0.00	0.00	0.00	0.00
11957.5	55.30	2.72	7.83	3.50	85.60	30.50	55.10	98.70	1.30	0.00	0.50	1.81
11958.0	56.00	2.73	8.69	3.83	71.40	31.30	40.10	84.40	15.60	0.01	0.50	23.09
11958.5	58.00	2.73	9.38	3.94	64.20	33.70	30.50	77.20	22.80	0.01	0.50	34.83
11959.0	61.60	2.73	9.51	3.66	67.00	37.90	29.10	80.00	20.00	0.01	0.50	28.36
11959.5	60.10	2.73	9.19	3.67	68.20	36.10	32.10	81.20	18.80	0.01	0.50	26.73
11960.0	52.50	2.72	8.60	4.09	63.10	27.50	35.60	76.10	23.90	0.01	0.50	37.82
11960.5	45.00	2.72	7.77	4.28	61.50	20.20	41.30	74.50	25.50	0.01	0.50	42.30
11961.0	42.40	2.72	7.50	4.32	62.90	18.00	44.80	75.90	24.10	0.01	0.50	40.39
11961.5	48.70	2.72	8.29	4.25	64.00	23.70	40.30	77.10	22.90	0.01	0.50	37.85
11962.0	54.70	2.72	8.84	4.01	65.70	29.90	35.80	78.70	21.30	0.01	0.50	33.02
11962.5	54.50	2.72	8.21	3.73	67.30	29.70	37.60	80.30	19.70	0.01	0.50	28.52
11963.0	58.60	2.73	8.15	3.38	70.50	34.30	36.20	83.50	16.50	0.01	0.50	21.58
11963.5	66.00	2.73	9.47	3.22	66.80	43.50	23.30	79.90	20.10	0.01	0.50	25.19
11964.0	64.60	2.73	10.43	3.69	56.50	41.80	14.70	69.50	30.50	0.01	0.50	43.60
11964.5	56.50	2.73	10.32	4.49	48.70	31.90	16.80	61.70	38.30	0.02	0.50	66.71
11965.0	52.80	2.72	10.39	4.90	47.50	27.90	19.60	60.50	39.50	0.02	0.50	75.12
11965.5	55.80	2.73	11.24	4.97	49.20	31.20	18.10	62.30	37.70	0.02	0.50	72.71
11966.0	61.40	2.73	11.69	4.52	56.20	37.60	18.50	69.20	30.80	0.01	0.50	53.97
11966.5	61.10	2.73	11.03	4.29	61.90	37.30	24.60	74.90	25.10	0.01	0.50	41.76
11967.0	60.20	2.73	10.18	4.05	69.20	36.30	33.00	82.30	17.70	0.01	0.50	27.84
11967.5	60.60	2.73	9.63	3.80	76.90	36.70	40.20	89.90	10.10	0.00	0.50	14.86
11968.0	54.70	2.72	8.59	3.89	77.80	29.90	47.90	90.80	9.20	0.00	0.50	13.85
11968.5	49.50	2.72	7.61	3.84	80.90	24.50	56.40	94.00	6.00	0.00	0.50	9.01
11969.0	52.40	2.72	7.72	3.68	85.30	27.50	57.80	98.30	1.70	0.00	0.50	2.39
11969.5	53.00	2.72	7.56	3.55	89.30	28.10	61.30	100.00	0.00	0.00	0.00	0.00
11970.0	47.00	2.72	6.56	3.48	93.30	22.10	71.30	100.00	0.00	0.00	0.00	0.00
11970.5	42.50	2.72	5.58	3.21	100.00	18.10	81.90	100.00	0.00	0.00	0.00	0.00
11971.0	43.40	2.72	5.18	2.93	100.00	18.90	81.10	100.00	0.00	0.00	0.00	0.00
11971.5	45.10	2.72	5.40	2.96	100.00	20.30	79.70	100.00	0.00	0.00	0.00	0.00
11972.0	47.20	2.72	5.60	2.96	100.00	22.30	77.70	100.00	0.00	0.00	0.00	0.00
11972.5	50.20	2.72	5.75	2.87	100.00	25.20	74.80	100.00	0.00	0.00	0.00	0.00
11973.0	49.80	2.72	5.73	2.88	100.00	24.80	75.20	100.00	0.00	0.00	0.00	0.00
11973.5	48.10	2.72	5.50	2.85	100.00	23.10	76.90	100.00	0.00	0.00	0.00	0.00
11974.0	48.00	2.72	5.65	2.94	100.00	23.10	76.90	100.00	0.00	0.00	0.00	0.00
11974.5	50.70	2.72	5.84	2.88	100.00	25.70	74.30	100.00	0.00	0.00	0.00	0.00
11975.0	51.80	2.72	5.61	2.71	100.00	26.80	73.20	100.00	0.00	0.00	0.00	0.00
11975.5	50.60	2.72	5.23	2.58	100.00	25.60	74.40	100.00	0.00	0.00	0.00	0.00
11976.0	51.20	2.72	5.01	2.45	100.00	26.20	73.80	100.00	0.00	0.00	0.00	0.00
11976.5	50.80	2.72	5.03	2.48	100.00	25.80	74.20	100.00	0.00	0.00	0.00	0.00
11977.0	48.90	2.72	5.10	2.61	100.00	23.90	76.10	100.00	0.00	0.00	0.00	0.00

Task 7.10 - Log Analysis of the Rogersville Shale Wells

Appendix 3. *Log Analysis of the Chesapeake LAW 1 Northup Well*

Depth (ft KB)	V_{clay} (%)	Rho_{ma} (gm/cc)	Phi_t (%)	Phi_e (%)	Sw_{Archie} (%)	Sw_b (%)	Sw_f (%)	Sw_t (%)	S_{hc} (So+Sg) (%)	$SoPhi_e$ (interval)	h (ft)	$SoPhi_eh$
11977.5	49.60	2.72	5.19	2.61	100.00	24.60	75.40	100.00	0.00	0.00	0.00	0.00
11978.0	51.10	2.72	5.30	2.59	100.00	26.10	73.90	100.00	0.00	0.00	0.00	0.00
11978.5	50.50	2.72	5.36	2.65	100.00	25.50	74.50	100.00	0.00	0.00	0.00	0.00
11979.0	54.90	2.72	5.65	2.55	100.00	30.20	69.80	100.00	0.00	0.00	0.00	0.00
11979.5	57.50	2.73	5.99	2.54	100.00	33.10	66.90	100.00	0.00	0.00	0.00	0.00
11980.0	50.80	2.72	5.39	2.65	100.00	25.80	74.20	100.00	0.00	0.00	0.00	0.00
11980.5	43.10	2.72	4.29	2.44	100.00	18.60	81.40	100.00	0.00	0.00	0.00	0.00
11981.0	40.10	2.72	4.03	2.41	100.00	16.10	83.90	100.00	0.00	0.00	0.00	0.00
11981.5	42.40	2.72	4.37	2.52	100.00	18.00	82.00	100.00	0.00	0.00	0.00	0.00
11982.0	50.00	2.72	5.04	2.52	100.00	25.00	75.00	100.00	0.00	0.00	0.00	0.00
11982.5	57.00	2.73	6.04	2.60	100.00	32.50	67.50	100.00	0.00	0.00	0.00	0.00
11983.0	61.30	2.73	6.56	2.54	100.00	37.60	62.40	100.00	0.00	0.00	0.00	0.00
11983.5	61.30	2.73	6.16	2.38	100.00	37.60	62.40	100.00	0.00	0.00	0.00	0.00
11984.0	59.30	2.73	5.83	2.37	100.00	35.20	64.80	100.00	0.00	0.00	0.00	0.00
11984.5	60.70	2.73	6.00	2.36	100.00	36.80	63.20	100.00	0.00	0.00	0.00	0.00
11985.0	63.30	2.73	5.90	2.17	100.00	40.10	59.90	100.00	0.00	0.00	0.00	0.00
11985.5	60.90	2.73	5.97	2.34	100.00	37.00	63.00	100.00	0.00	0.00	0.00	0.00
11986.0	58.00	2.73	6.56	2.75	100.00	33.70	66.30	100.00	0.00	0.00	0.00	0.00
11986.5	61.90	2.73	6.91	2.63	100.00	38.30	61.70	100.00	0.00	0.00	0.00	0.00
11987.0	62.70	2.73	6.60	2.46	100.00	39.40	60.60	100.00	0.00	0.00	0.00	0.00
11987.5	55.70	2.72	5.96	2.64	100.00	31.00	69.00	100.00	0.00	0.00	0.00	0.00
11988.0	48.90	2.72	5.52	2.82	100.00	23.90	76.10	100.00	0.00	0.00	0.00	0.00
11988.5	46.90	2.72	5.00	2.65	100.00	22.00	78.00	100.00	0.00	0.00	0.00	0.00
11989.0	50.30	2.72	4.78	2.38	100.00	25.30	74.70	100.00	0.00	0.00	0.00	0.00
11989.5	55.10	2.72	5.29	2.38	100.00	30.30	69.70	100.00	0.00	0.00	0.00	0.00
11990.0	50.80	2.72	5.09	2.51	100.00	25.80	74.20	100.00	0.00	0.00	0.00	0.00
11990.5	43.70	2.72	4.58	2.58	100.00	19.10	80.90	100.00	0.00	0.00	0.00	0.00
11991.0	44.60	2.72	4.88	2.70	100.00	19.90	80.10	100.00	0.00	0.00	0.00	0.00
11991.5	47.70	2.72	5.21	2.73	100.00	22.80	77.20	100.00	0.00	0.00	0.00	0.00
11992.0	51.40	2.72	5.33	2.59	100.00	26.40	73.60	100.00	0.00	0.00	0.00	0.00
11992.5	59.10	2.73	5.47	2.24	100.00	34.90	65.10	100.00	0.00	0.00	0.00	0.00
11993.0	60.90	2.73	5.49	2.15	100.00	37.10	62.90	100.00	0.00	0.00	0.00	0.00
11993.5	57.40	2.73	5.53	2.36	100.00	32.90	67.10	100.00	0.00	0.00	0.00	0.00
11994.0	60.20	2.73	5.72	2.28	100.00	36.20	63.80	100.00	0.00	0.00	0.00	0.00
11994.5	65.50	2.73	5.87	2.03	100.00	42.90	57.10	100.00	0.00	0.00	0.00	0.00
11995.0	65.80	2.73	5.88	2.01	100.00	43.30	56.70	100.00	0.00	0.00	0.00	0.00
11995.5	63.20	2.73	5.90	2.17	100.00	40.00	60.00	100.00	0.00	0.00	0.00	0.00
11996.0	64.60	2.73	6.19	2.19	100.00	41.70	58.30	100.00	0.00	0.00	0.00	0.00
11996.5	66.50	2.73	6.26	2.10	100.00	44.20	55.80	100.00	0.00	0.00	0.00	0.00
11997.0	62.50	2.73	5.59	2.10	100.00	39.10	60.90	100.00	0.00	0.00	0.00	0.00
11997.5	51.90	2.72	4.71	2.27	100.00	26.90	73.10	100.00	0.00	0.00	0.00	0.00
11998.0	39.30	2.72	4.01	2.43	100.00	15.40	84.60	100.00	0.00	0.00	0.00	0.00
11998.5	38.40	2.72	3.79	2.33	100.00	14.70	85.30	100.00	0.00	0.00	0.00	0.00
11999.0	46.00	2.72	4.13	2.23	100.00	21.10	78.90	100.00	0.00	0.00	0.00	0.00
11999.5	47.60	2.72	4.24	2.22	100.00	22.60	77.40	100.00	0.00	0.00	0.00	0.00
12000.0	45.90	2.72	3.96	2.14	100.00	21.10	78.90	100.00	0.00	0.00	0.00	0.00

4. DEVELOPMENT STRATEGY PLAN*

By Co-PI's John Hickman and David Harris

University of Kentucky – Kentucky Geological Survey

Lexington, Ky

(*Note: Because of the ending of this project prior to Budget Period 2, this Development Strategy Plan is based solely on the results of research performed in Budget Period 1.)

Current State of the Conasauga/Rogersville Shale Unconventional Oil and Gas Play

Although oil and gas shows have been reported in wells penetrating the Conasauga Group since the 1940's, exploration targeting the Rogersville as an unconventional reservoir only began in 2013 with the Bruin Exploration #1 Sylvia Young well in Lawrence County, Ky.

Five more wells targeting the Rogersville were drilled between 2013 and 2017: Bruin Exploration #1 Walbridge Holdings, Cabot Oil and Gas #50 Amherst Industries, Horizontal Tech Energy #572360 Caudill, and the Chesapeake Appalachia #LAW-1 J. Stephens and the #LAW-1 Northup Estate wells. No additional wells have been drilled since 2017. Out of the 6 wells drilled, only one was put on production (#50 Amherst Industries), which produced just under 340 MMCF over 30 months before being plugged. All four of the companies with Rogersville wells have now released their leased acreage and exited the play. There are currently no new Conasauga wells permitted for drilling in Kentucky or West Virginia.

Conasauga Play - Limiting Factors for Success

Although the Conasauga Shale Research Consortium project could not perform all of the planned research due to the early closing of the project due to outside forces, the team was able to learn quite a bit about the geology and hydrocarbon production of the Conasauga Shales. Based upon our research, these are the factors limiting success:

Reduced organic "richness" – Although this is directly related to the source rock volume issues described below, even the "sweet spot" of the Rogersville has relatively low TOC when compared to other unconventional shale target formations (e.g.- Marcellus Shale can contain over 15% TOC). The relatively thin organic target interval contained 1-4% TOC (with no values recorded over 5%), but the rest of the Rogersville averages around 0.4% TOC.

Reduced source rock volume – Although all six members of the Conasauga Group (consisting of over 5,000 feet of sediments in Lawrence County, Kentucky) were deposited in the Rome Trough, only the Rogersville Shale contains "source-rock quality" units that could produce hydrocarbons. Within the Rogersville itself, a total thickness of less than 140' of shale (organic "sweet spot") contains >1 wt% Total Organic Carbon (%TOC). This limited source rock volume reduces the theoretical amount of original oil/gas-in-place estimates, therefore limiting ultimate recovery.

Deep, compartmentalized reservoir – In the current, four county Play area (Lawrence and Johnson Counties, Kentucky, and Wayne and Putnam Counties, West Virginia), the top of the Rogersville

Shale is 10,000-15,000 feet deep. Because of the heavily faulted Cambrian strata in the Rome Trough, these depths increase uncertainties in local stratigraphic elevations for a well's landing point, distances to the nearest fault or fracking barrier, or to accurately target the lateral. Additionally, these depths also require larger drilling rigs and mud pumps that is typically used in Kentucky to drill to those depths, raising drilling costs for the well.

Expanding-clay issues hamper drilling/completion – X-ray diffraction mineralogy of drill cuttings and rotary sidewall cores indicate that parts of the Rogersville have a clay content that is composed of more than 18% expandable illite/smectite clays. These expandable clays can create hole collapse issues from caving into the borehole, as well as reservoir permeability loss if fresh water is used in drilling mud or completion fluids within the Rogersville. To avoid as many issues as possible, using oil-based drilling muds and brine-based completion fluids is highly recommended.

Accomplishments of the Conasauga Shale Research Consortium

Although we were unable to drill a new research well and test innovative completion designs, the CSRC has made numerous accomplishments that further the knowledge of the unconventional resource capacity of the Cambrian Conasauga Group of eastern Kentucky and southern West Virginia. A partial list of our accomplishments include:

- Producing a compilation of modern geologic, geochemical, geophysical, and geomechanical datasets for the six existing Rogersville UOG wells from four exploration companies which would never have been made public if not for this project.
- Mapped the depth, thickness, distribution, organic content, and thermal maturity of the Rogersville
- Analyzed the mineralogical and chemical composition, as well as the common porosity permeability values of the Rogersville
- Identified and characterized the organic-rich "sweet spot" interval in the Rogersville Shale
- Analyzed the geochemical and sedimentological makeup of core samples to determine environment of deposition with respect to organic preservation
- A "post mortem" analysis of recent well designs and their results, with suggestions for possible improvements
- A 16-month background seismicity evaluation of the Play region to aid in preventing future induced seismicity

Future of the Rogersville UOG Play

Although the Play appears to be not economic at this time, future increases in oil/gas prices or technology-driven decreases in drilling/completion costs could make it an attractive target, again. This report can be used by future exploration companies to evaluate and develop the play when prices or profitability improves. This "head start" on data and information will allow for faster, and hopefully more profitable, Conasauga/Rogersville Play development.